NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3629

INVESTIGATION OF THE EFFECTS OF GROUND PROXIMITY AND PROPELLER POSITION ON THE EFFECTIVENESS OF A WING WITH LARGE-CHORD SLOTTED FLAPS IN REDIRECTING PROPELLER SLIPSTREAMS DOWNWARD FOR VERTICAL TAKE-OFF

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SUMMARY

An investigation of the effects of ground proximity and propeller position on the effectiveness of a wing equipped with large-chord slotted flaps in redirecting the slipstreams from large-diameter propellers downward for vertical take-off has been conducted in a static-thrust facility at the Langley Aeronautical Laboratory.

The results indicate that, with the propeller thrust axis on the wing chord plane, both the angle through which the slipstream is deflected and the ratio of resultant force to thrust are reduced as the ground is approached. At positions nearest the ground some of the loss in resultant force is regained. Lowering the thrust axis below the wing chord plane reduces the adverse effects of the ground and also reduces the large diving moments associated with the slotted-flap arrangement. The static-thrust efficiency of the propellers is slightly reduced by the ground effect.

INTRODUCTION

Recent work on wing configurations designed to redirect propeller slipstreams downward for vertical take-off has demonstrated that the redirected-slipstream principle can be used to provide direct lift for aircraft without the necessity of inclining either the fuselage or the propellers through large angles with respect to the ground. The free-flight characteristics, during take-off, hovering, and landing, of a model that operates on the redirected-slipstream principle through use of a single large-chord plain flap and a retractable cascade of vanes have been studied by the Langley free-flight tunnel section. (See ref. 1.)

The 7- by 10-Foot Tunnels Branch of the Langley Aeronautical Laboratory is conducting a program aimed at developing a simple wing configuration that will be capable of redirecting the slipstream (refs. 2 to 4). Most of the development work on these configurations has been done without simulation of the ground and, therefore, the results represent hovering characteristics at some distance above the ground. The flight tests reported in reference 1 showed a tendency of the model to move forward as it approached the ground, which indicated that the angle through which the slipstream was deflected was reduced near the ground. Accordingly, an investigation has been undertaken with the slotted-flap wing of reference 2 to determine the effects of proximity to the ground on the turning effectiveness of the configuration and to study the effects of propeller position on the turning effectiveness both in and out of the ground-effect region.

SYMBOLS

The symbols used in the present paper are defined below. The positive sense of forces, moments, angles, and distances are indicated in figure 1.

c	wing chord, ft
$\bar{c}$	mean aerodynamic chord of wing, ft
D	propeller diameter, ft
F	resultant force, lb
h	distance from inboard end of flap trailing edge to ground board, ft
i_w	wing incidence, deg
L	lift, lb
M	pitching moment, ft-lb
M_p	propeller pitching moment, ft-lb
N_p	propeller normal force, lb
n	propeller rotational speed, rps

P	propeller shaft power, $2\pi nQ/550$, hp
Q	torque, ft-lb
T	total propeller thrust, lb
X	longitudinal force, lb
x	longitudinal distance from propeller to wing leading edge, ft (See fig. 1.)
z	vertical distance from thrust axis to wing chord plane, ft (See fig. 1.)
δ_f	flap deflection
η''	static-thrust efficiency, $\dfrac{T^{3/2}}{1100P\sqrt{\frac{\rho}{2}\frac{\pi}{4}D^2}}$
θ	inclination of resultant force vector from thrust axis, $\tan^{-1}\frac{L}{X}$, deg
ρ	mass density of air, slugs/cu ft

Subscripts:

i	inboard propeller
o	outboard propeller
30	30-percent-chord flap
60	60-percent-chord flap

APPARATUS AND METHODS

A drawing of the model used in most of the tests and its pertinent dimensions are shown in figure 2 and a photograph of the model mounted for testing is shown in figure 3. Except for the propellers, the model was the same as that used for the investigation reported in reference 2. The geometric characteristics of the wing and propellers are given in the following table:

Wing:

Area (semispan), sq ft	5.125
Span (semispan), ft	3.416
Mean aerodynamic chord, ft	1.514
Root chord, ft	1.75
Tip chord, ft	1.25
Airfoil section	NACA 0015
Aspect ratio	4.55
Taper ratio	0.714

Propellers:

Diameter, ft	2.0
Nacelle diameter, ft	0.33
Airfoil section	Clark Y
Solidity (each propeller)	0.10

The ordinates of the flaps were derived from the slotted flap 2-h of reference 5 and are presented in table I. The slotted flaps were supported by external brackets which can be seen in figure 3. The cross section of the auxiliary-vane configuration, which is the same configuration tested in reference 2, is shown in figure 4. The vane was made of 1/8-inch sheet steel.

The propellers used in this investigation (fig. 3) had plan forms different from those used in the investigations of references 2 and 3. Molded Fiberglas and balsa-wood propeller blades were used so that possible propeller blade failures would be less likely to damage the strain-gage balances on which the motors and propellers were mounted. The propellers were driven by variable-frequency electric motors. During the tests, the propeller rotational speed was approximately 6,000 rpm, which gave a tip Mach number of 0.58. The speed of each motor was determined by observing a stroboscopic-type indicator, to which was fed the output frequency of a small alternator connected to the motor shaft. Because both motors were driven from a common power supply, their speeds were usually matched within 10 rpm. The outboard propeller rotated against the tip vortex (right-hand rotation on right wing) and the inboard propeller rotated in the opposite direction.

The motors were mounted inside aluminum-alloy nacelles by means of strain-gage beams in such a way that the propeller thrust and torque could be measured. The inboard nacelle was equipped with additional strain-gage instrumentation so that the propeller normal force and pitching moment could also be measured. In addition, the total lift, longitudinal force, and pitching moment of the model were measured on a balance at the root of the wing.

The tests to determine the effects of propeller location were conducted with a setup similar to the one shown in figure 5. For these tests, a single propeller was located at the same spanwise location as the inboard propeller shown in figure 2. Although the propeller was independently mounted for these tests, the propeller thrust has been included in the data presented. For purposes of comparison a few tests have been made with only the inboard propeller mounted on the wing.

The ground was simulated by a sheet of plywood, as shown in figure 3. All tests with the ground board were conducted with an angle of 20° between the ground plane and the thrust axis of the propellers. (See fig. 1.) Because the wing was tapered, the height h above the ground was defined, arbitrarily, as the distance from the inboard end of the flap trailing edge to the ground board.

The investigation was conducted in a static-thrust facility of the Langley Aeronautical Laboratory. All data presented were obtained at zero forward velocity with a thrust of 15 pounds from each propeller. Inasmuch as the tests were conducted under static conditions in a large room, none of the corrections that are normally applicable to wind-tunnel tests were applied.

RESULTS AND DISCUSSION

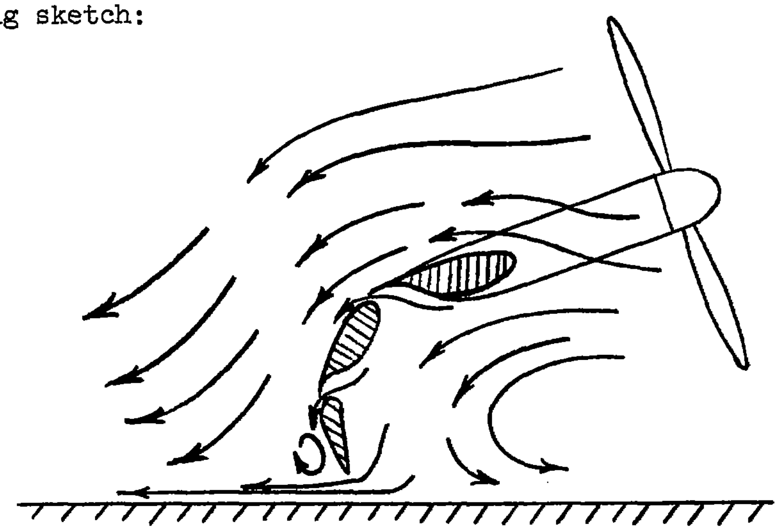
For the purposes of the discussion the configuration with the thrust axes of both propellers on the wing chord plane and with zero wing incidence is referred to as the basic configuration, and the configuration with the thrust axes of both propellers lowered 0.1D and with 5° wing incidence is referred to as the modified configuration.

Characteristics of Basic Configuration in the Ground-Effect Region

The characteristics of the basic configuration out of the ground-effect region have been investigated extensively and the results were reported in reference 2. The effect of proximity to the ground on the characteristics of this configuration with flap deflections $\delta_{f_{60}} = 50^{\circ}$ and $\delta_{f_{30}} = 40^{\circ}$, which gave good results for the model out of the ground-effect region, is presented in figure 6. The effect of the ground is characterized first by a loss in resultant force F as the ground is approached, next by a large loss in turning angle θ, and finally by an increase in resultant force at a position above the ground that would correspond to a reasonable clearance with an airplane at rest. For the basic configuration a loss in turning angle of about 20° is experienced. Other combinations of flap deflection (fig. 7) had little effect on the turning effectiveness when the model was in the position nearest the ground.

Reference 2 indicated that addition of the auxiliary vane shown in figure 4 effected an increase in the turning angles for the model out of the ground-effect region. The effect of the ground on the characteristics of this configuration is shown in figure 8. Comparison of figures 7 and 8 indicates that addition of the vane increases the turning angle for the model in the ground-effect region somewhat, but the turning is still much less than that obtained out of the ground-effect region.

Tuft studies indicated that the trailing-edge flap was completely stalled when the model was in the position nearest the ground. Also, more of the slipstream appeared to flow over the wing when the model was near the ground. The type of flow observed is shown in the following sketch:



Effect of Propeller Position

The tuft studies of the flow about the model suggested that, if the slipstream could be kept from escaping over the top of the wing, some improvement in the characteristics near the ground might be effected. This possibility in turn suggested that the relative position of the propeller with respect to the wing might be significant. In order to investigate such effects, it was found convenient to conduct the tests with only one propeller mounted on an independent support similar to the one shown in figure 5 so that the position of the propeller with respect to the wing could be easily shifted. The effect of the vertical position z/D of the propeller with respect to the chord plane of the wing is shown in figures 9 and 10 and the effect of longitudinal position x/D is shown in figure 11.

With the propeller close to the wing $(x/D = 0.25)$, lowering the thrust axis 0.125D below the wing chord plane is seen to effect a small increase in turning angle when the model is out of the ground-effect region and an appreciable increase when near the ground (fig. 9). Also, the ratio of resultant force to thrust is greater with the model near the ground than out of the ground-effect region. When the thrust axis is lowered to a position 0.25D below the wing chord plane, a further increase in turning angle is achieved with the model in the position nearest the ground; however, at positions out of the ground-effect region and at intermediate heights above the ground the turning is about the same for this configuration as for the configuration with the thrust axis 0.125D below the chord plane.

With the propeller in the longitudinal position corresponding to the basic configuration ($x/D = 0.42$), lowering the thrust axis 0.125D below the chord plane again effected a small increase in turning angle with the model out of the ground-effect region and an appreciable increase with the model near the ground (fig. 10). Further lowering of the thrust axis to a position 0.25D below the wing chord plane had little effect on the characteristics.

At a vertical position 0.125D below the wing chord plane, the turning characteristics appear to be relatively insensitive to the longitudinal position of the propeller (fig. 11), although the ratio of resultant force to thrust is slightly higher for the most forward position investigated.

Lowering the thrust axis (figs. 9 and 10) also reduces substantially the large diving moments associated with the slotted-flap configuration.

Comparison of Characteristics of One- and Two-Propeller Models

The ratios of resultant force to thrust shown in figures 9, 10, and 11 for one propeller independently mounted are appreciably lower than the values presented in reference 2 and in figures 6 and 7 of the present paper for the model with two propellers mounted on the wing. A comparison of the effect of various propeller-mounting arrangements on the turning characteristics of the wing out of the ground-effect region is shown in figures 12 and 13. The desirability of using a multiple-propeller arrangement for this configuration is apparent. The reasons for the difference between the data for the one- and two-propeller configurations are not known; however, the difference may be associated with the "bleeding" of part of the slipstream below the wing chord plane through the part of the slots outboard of the main slipstream where it cannot appreciably affect the upper part of the slipstream, or the difference may be a result of the lower effective aspect ratio of the wing immersed in the slipstream and the fact that the slipstream from a single propeller has more room to expand laterally than have the slipstreams from two propellers working side by side.

Tests with other wing-flap sections indicate that the effect of changing the number of propellers is a function of the flap configuration. For instance, with a configuration employing large-chord plain flaps and two auxiliary vanes (ref. 4), a change from two propellers to one propeller resulted in a loss in turning angle without much loss in resultant force. Also, data from tests on a different flap arrangement show only small differences between the characteristics with one or two propellers operating. These observations indicate that the differences shown in figures 12 and 13 and the reasons for these differences cannot be generalized.

Figures 12 and 13 indicate that changing the propeller mounting from an independent stand to the wing causes very little difference in the characteristics.

Characteristics of Modified Configuration

The turning angle achieved by the basic slotted-flap wing appears to be smaller than would be desired for a vertically rising airplane, inasmuch as a nose-up attitude of 30° would be required for hovering out of the ground-effect region and a still higher attitude would be required for take-off. The data of figures 9 and 10 indicate that with one propeller operating an increase in turning angle both in and out of the ground-effect region was obtained by lowering the thrust axis below the wing chord plane. In addition, the data of reference 2 indicated that positive incidence between the wing chord plane and the thrust axis increased the turning angle. Accordingly, these two modifications (5° of wing incidence and both thrust lines lowered 0.1D) were incorporated into the model. A comparison between results with the original and modified configurations is shown in figure 14. The expected improvements near the ground are shown; however, the desired improvements in characteristics out of the ground-effect region were not realized. Tuft studies indicated that flow at the rear ends of the nacelles was separating badly and it appears likely that this separation was "contaminating" the flow through the slots. Attempts to reduce the separation were unsuccessful largely because the length of the electric motors used to drive the propellers did not leave sufficient distance between the rear of the nacelles and the first flap slot to allow adequate fairing of the nacelle into the wing.

Effect of Ground on Propeller Characteristics

The normal force and pitching moment of the inboard propeller and the static thrust efficiency of each propeller, both in and out of the ground-effect region, are presented in figure 15. The measurements of the propeller normal force and pitching moment are complicated by the fact that small forces are being measured by strain-gage beams which must also measure the much larger propeller thrust and support the weight of the motors. The comparison of the propeller normal forces and pitching moment for the model in and out of the ground-effect region shows only small effects of proximity to the ground and these differences appear to be largely within the accuracy of the measuring equipment. In any event, the values shown are small when compared with the normal force and pitching moment that would be expected at high attitudes and low forward speeds as shown in reference 6.

The effect of the ground on the static-thrust efficiency of each propeller is also shown in figure 15. A loss of about 3 to 5 percent in efficiency is shown. This loss in efficiency is especially important for an airplane that must derive all its lift for take-off by converting the engine power to static thrust.

It is of interest to compare the effect of the ground on propeller characteristics for the wing-propeller configurations that have been discussed with the effect obtained for the helicopter condition in which a propeller, with thrust axis vertical, is allowed to approach the ground. In order to simulate the latter condition, the propeller and motor used in the setup shown in figure 5 were operated at various distances from the ground board. As was expected, the helicopter arrangement provided a large increase in static-thrust efficiency at heights above the ground of 0.50D or less. (See fig. 16.)

CONCLUSIONS

The investigation of the effects of proximity to the ground and propeller position on the effectiveness of a wing equipped with large-chord slotted flaps in redirecting propeller slipstreams downward for vertical take-off indicates the following conclusions:

1. With the propeller thrust axis on the wing chord plane, both the angle through which the slipstream is deflected and the ratio of resultant force to thrust are reduced as the ground is approached. At the positions nearest the ground, some of the loss in resultant force is regained.

2. Lowering the thrust axis below the wing chord plane helps to reduce the adverse effects of the ground. Lowering the thrust axis also reduces the large diving moments associated with this flap arrangement.

3. For the wing-propeller configurations of this investigation, the static-thrust efficiency of the propellers is reduced slightly by ground effect, which is in contrast to a large increase obtained for helicopter condition in which the propeller axis is normal to the ground.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., December 12, 1955.

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2. Kuhn, Richard E., and Draper, John W.: Investigation of Effectiveness of Large-Chord Slotted Flaps in Deflecting Propeller Slipstreams Downward for Vertical Take-Off and Low-Speed Flight. NACA TN 3364, 1955.

3. Draper, John W., and Kuhn, Richard E.: Some Effects of Propeller Operation and Location on Ability of a Wing With Plain Flaps To Deflect Propeller Slipstreams Downward for Vertical Take-Off. NACA TN 3360, 1955.

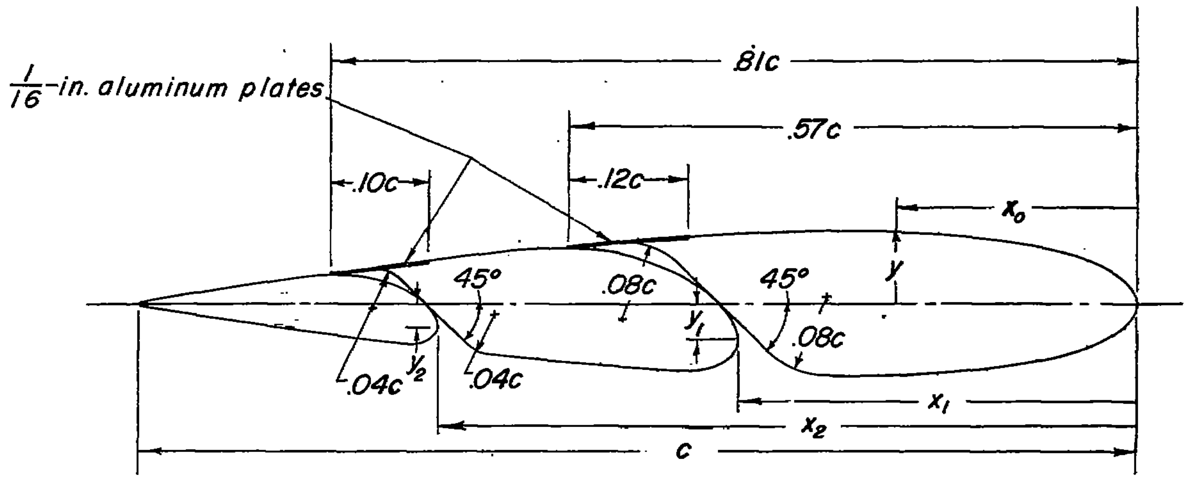
4. Kuhn, Richard E., and Draper, John W.: An Investigation of a Wing-Propeller Configuration Employing Large-Chord Plain Flaps and Large-Diameter Propellers for Low-Speed Flight and Vertical Take-Off. NACA TN 3307, 1954.

5. Wenzinger, Carl J., and Harris, Thomas A.: Wind-Tunnel Investigation of an N.A.C.A. 23012 Airfoil With Various Arrangements of Slotted Flaps. NACA Rep. 664, 1939.

6. Draper, John W., and Kuhn, Richard E.: Investigation of the Aerodynamic Characteristics of a Model Wing-Propeller Combination and of the Wing and Propeller Separately at Angles of Attack Up to 90°. NACA TN 3304, 1954.

TABLE I

DETAILS OF THE WING AND FLAP SECTIONS



WING AND FLAP ORDINATES

Station x_o, percent chord	Ordinate, y, percent chord					
	Wing, NACA 0015		0.60c flap		0.30c flap	
	Upper	Lower	Upper	Lower	Upper	Lower
0	0	0	-----	-----	-----	-----
1.25	2.37	-2.37	-----	-----	-----	-----
2.50	3.27	-3.27	-----	-----	-----	-----
5.00	4.40	-4.40	-----	-----	-----	-----
7.50	5.25	-5.25	-----	-----	-----	-----
10.00	5.85	-5.85	-----	-----	-----	-----
15.00	6.68	-6.68	-----	-----	-----	-----
20.00	7.17	-7.17	-----	-----	-----	-----
25.00	7.43	-7.43	-----	-----	-----	-----
30.00	7.50	-7.50	-----	-----	-----	-----
40.00	7.25	-7.25	-3.50	-3.50	-----	-----
40.50	----	-----	-2.00	-5.10	-----	-----
41.00	----	-----	-1.10	-5.70	-----	-----
42.00	----	-----	.20	-6.30	-----	-----
44.00	----	-----	1.80	-6.80	-----	-----
46.00	----	-----	3.00	-6.90	-----	-----
48.00	----	-----	3.90	-6.80	-----	-----
50.00	6.62	-6.62	4.60	-6.62	-----	-----
54.00	----	-----	5.60	-----	-----	-----
58.00	----	-----	5.70	-----	-----	-----
60.00	5.70	-5.70	5.70	-----	-----	-----
70.00	4.58	-4.58	-----	-----	-2.30	-2.30
70.50	----	-----	-----	-----	-1.00	-3.40
71.00	----	-----	-----	-----	-.40	-3.70
72.00	----	-----	-----	-----	.60	-4.00
74.00	----	-----	-----	-----	1.70	-4.00
76.00	----	-----	-----	-----	2.50	-----
78.00	----	-----	-----	-----	2.90	-----
80.00	3.28	-3.28	-----	-----	3.00	-----
82.00	----	-----	-----	-----	2.90	-----
90.00	1.81	-1.81	-----	-----	-----	-----
95.00	1.01	-1.01	-----	-----	-----	-----
100.00	.16	-.16	-----	-----	-----	-----

PATH OF THE FLAP NOSE

[Value in percent chord]

δ_f, deg	0.60c flap		0.30c flap	
	x_1	y_1	x_2	y_2
0	40.0	-3.5	70.0	-2.3
10	44.0	-2.0	72.5	-1.5
20	48.0	-1.5	74.7	-1.2
30	52.5	-1.5	77.2	-1.2
40	54.8	.5	79.2	-.2
50	56.0	2.0	80.4	.7
60	57.7	2.5	81,0	1.0
70	59.0	2.8	81.3	2.0

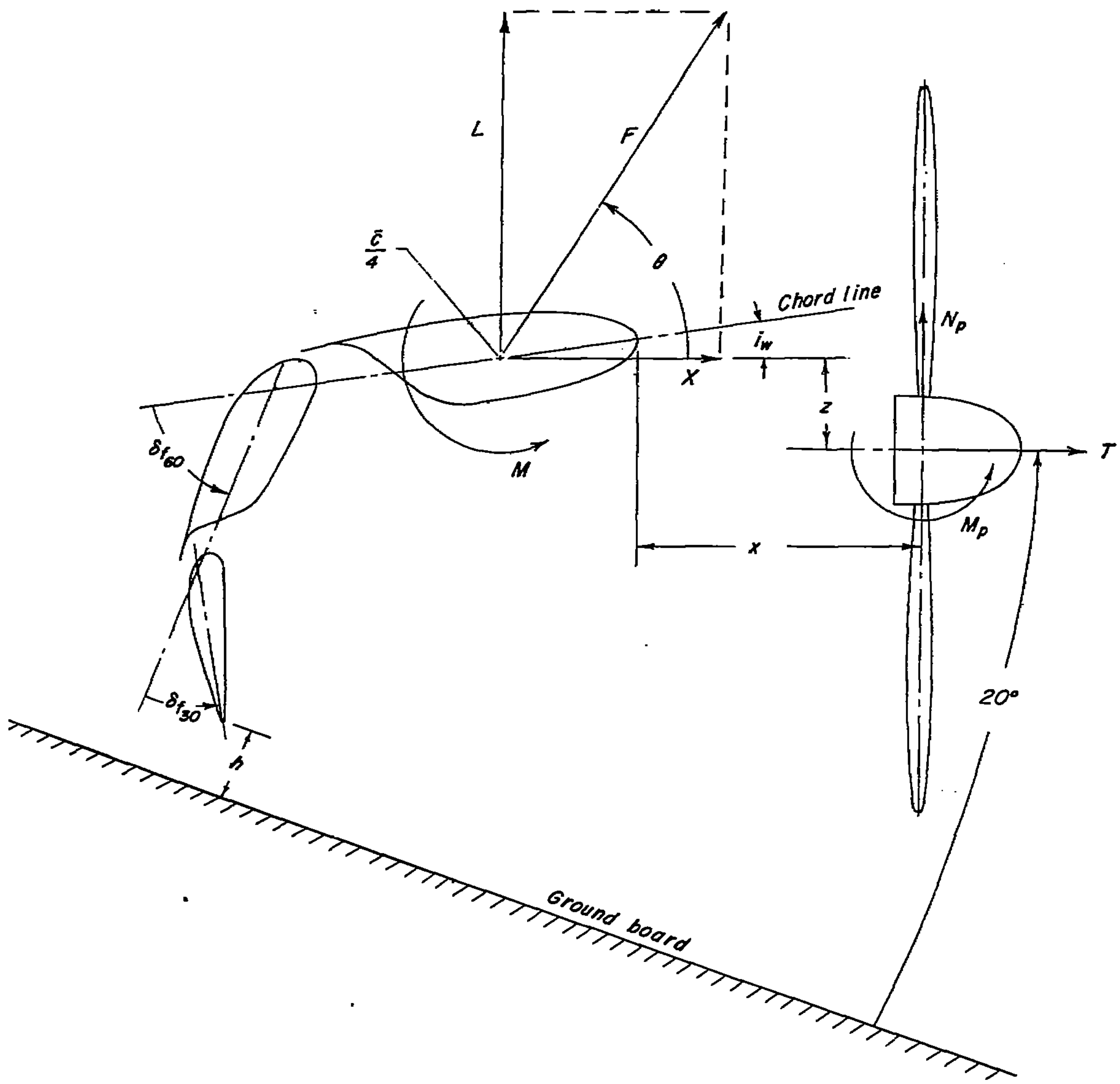


Figure 1.- Conventions used to define positive sense of forces, moments, angles, and distances.

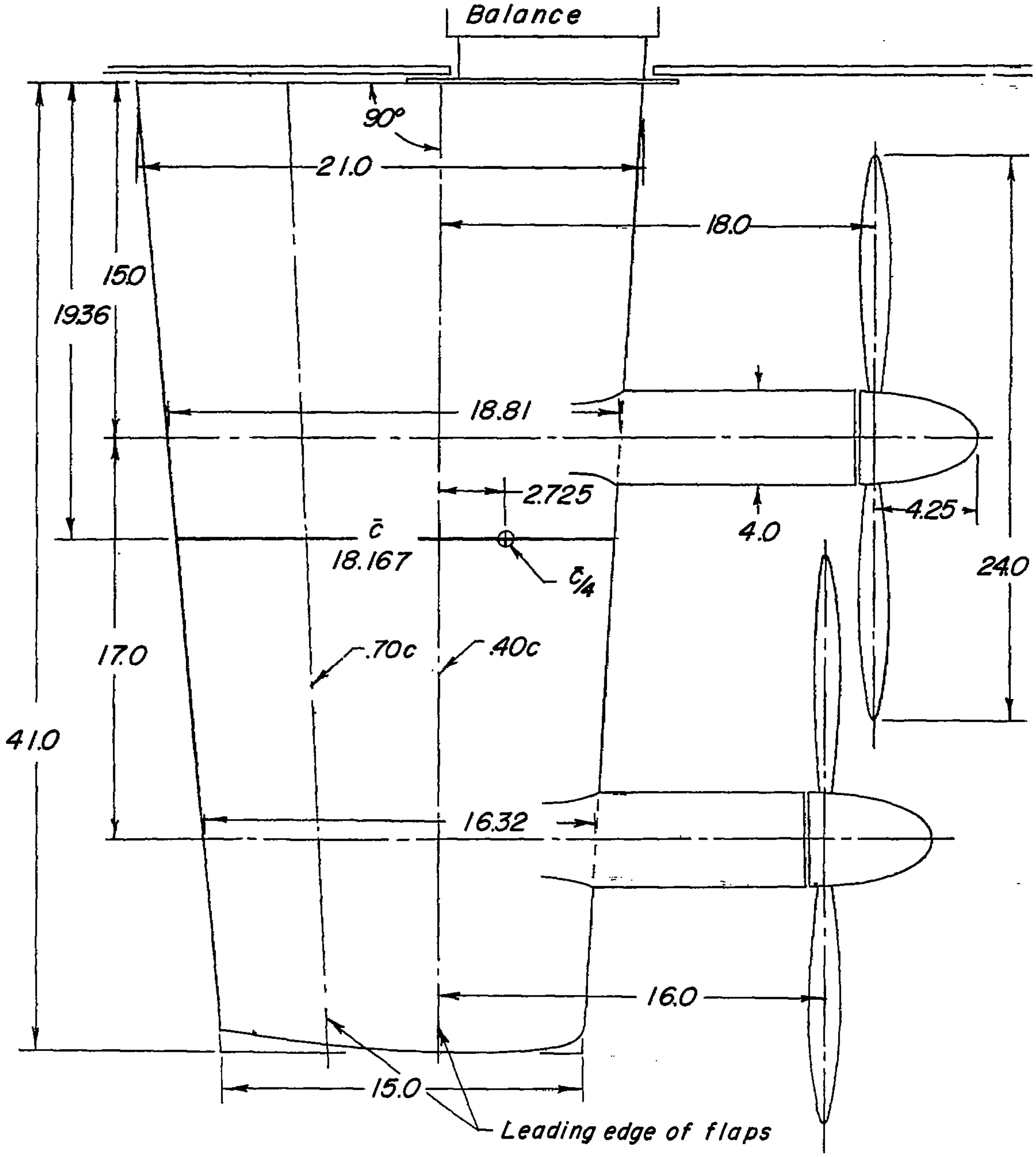


Figure 2.- Plan view of model. All dimensions in inches.

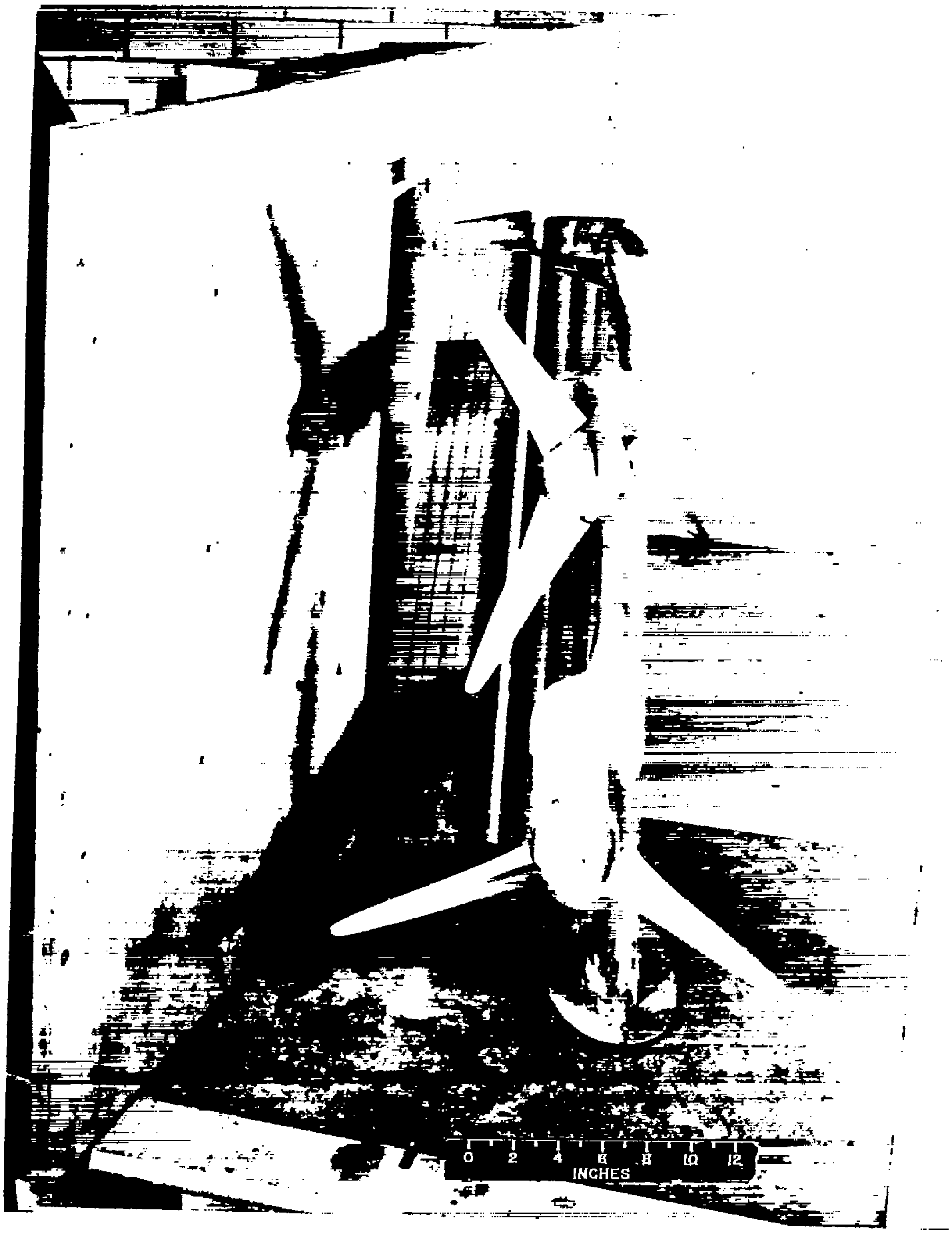


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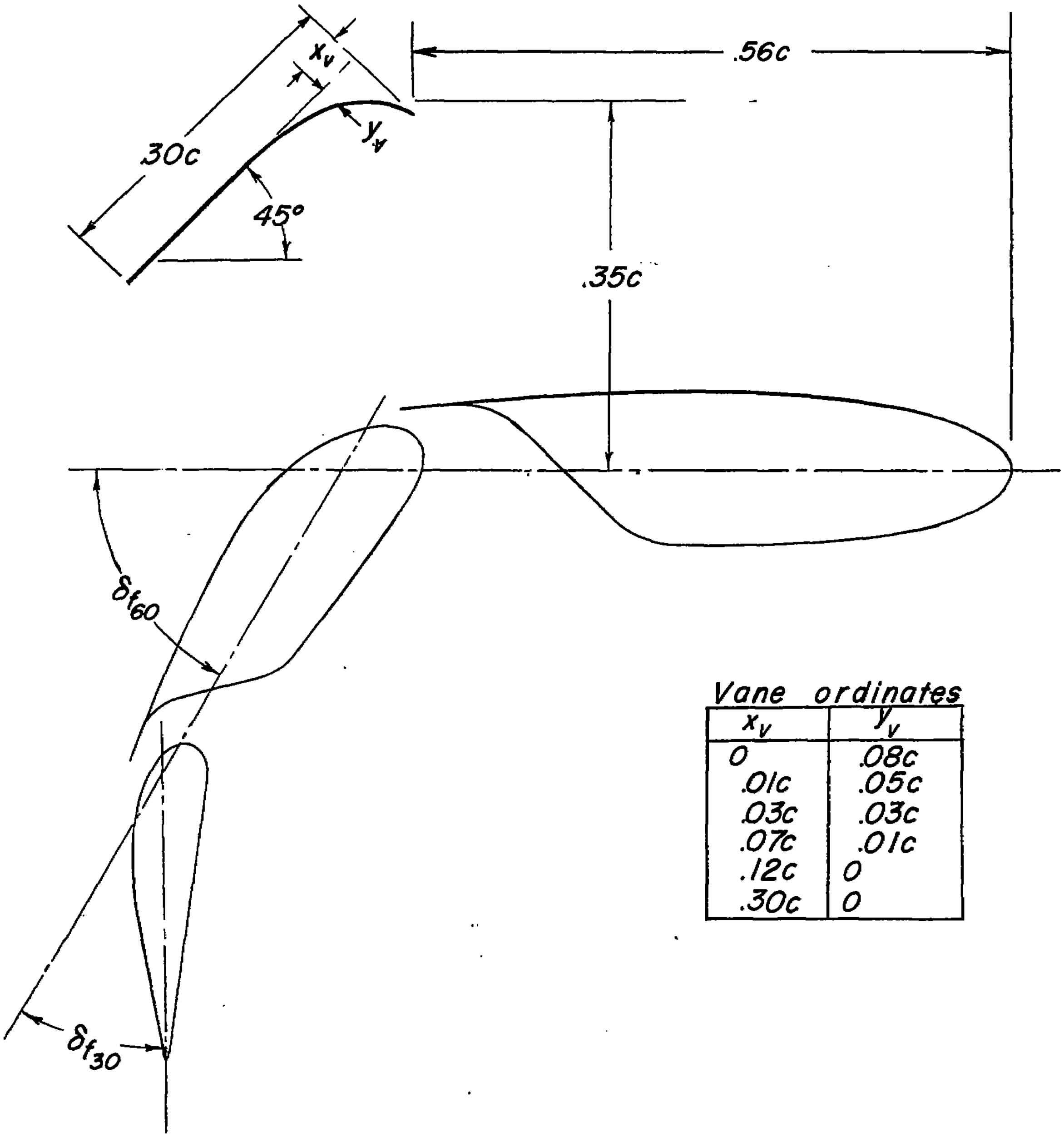
Figure 3.- Model installed on static-thrust stand with ground board in position nearest ground $\left(\frac{h}{D} = 0.08\right)$. Modified configuration; $\frac{z}{D} = 0.10$; $i_w = 5^{\circ}$.



Vane ordinates

x_v	y_v
0	.08c
.01c	.05c
.03c	.03c
.07c	.01c
.12c	0
.30c	0

Figure 4.- Cross section of the auxiliary-vane configuration.

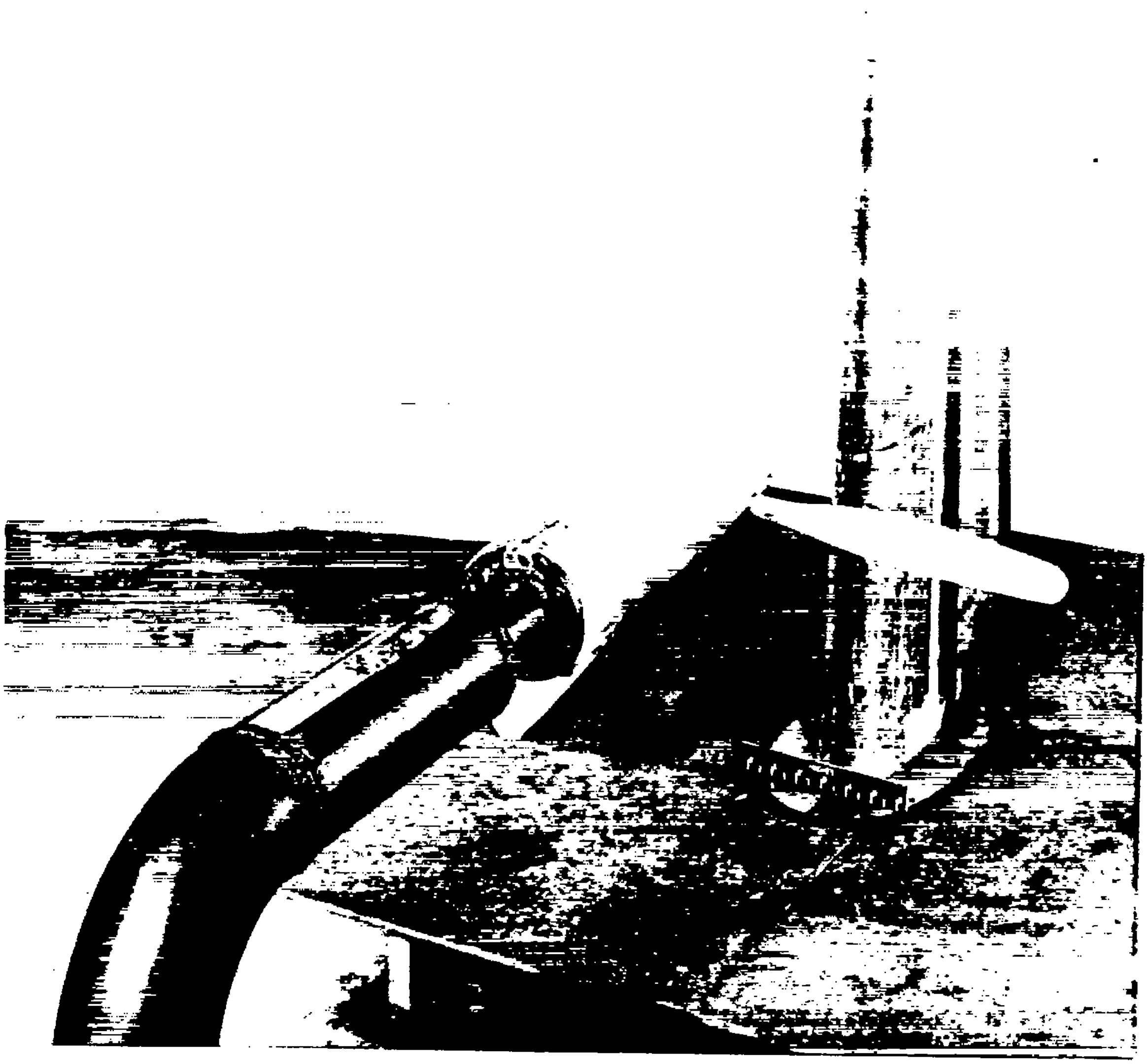


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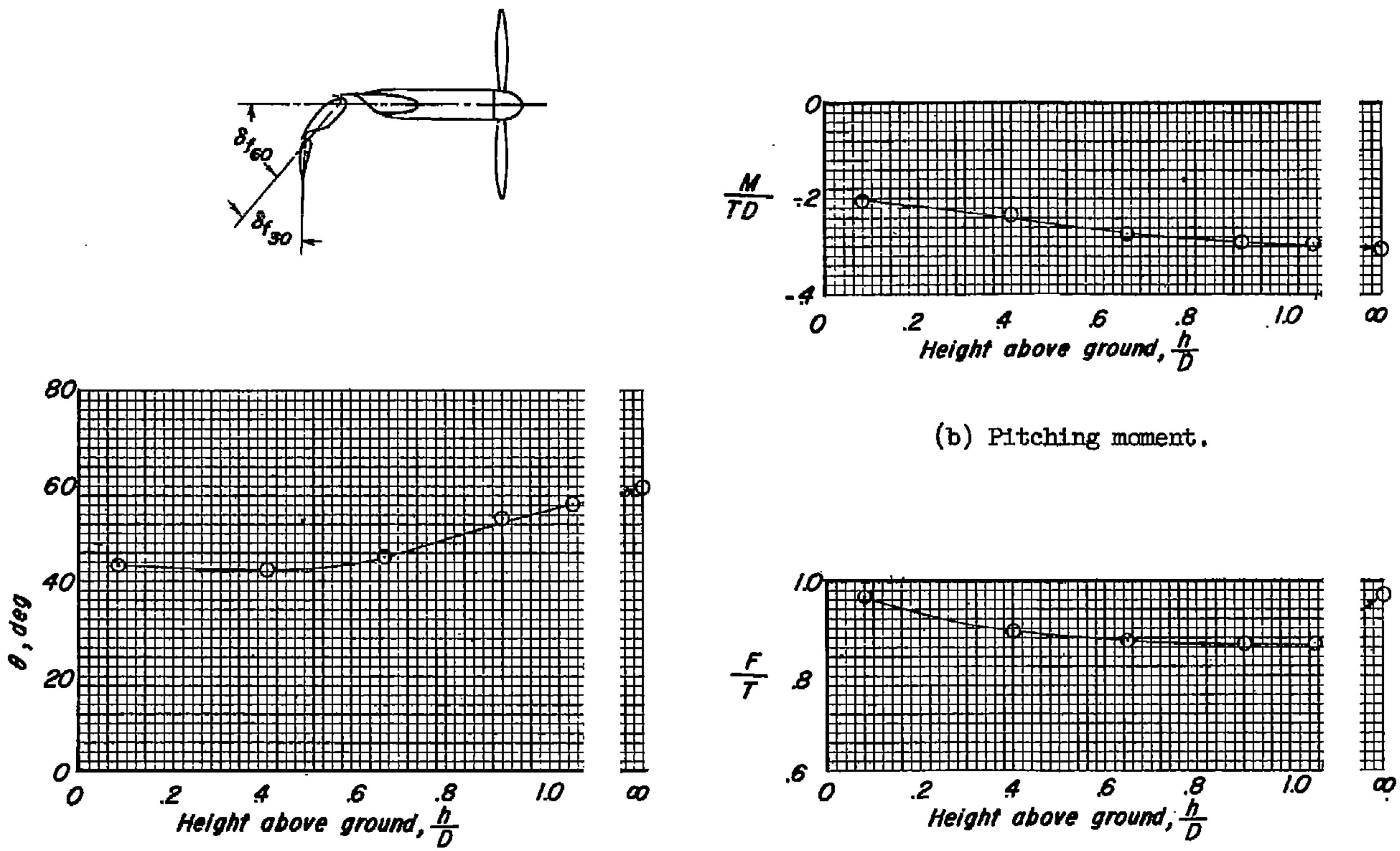
Figure 5.- Static-thrust setup of reference 3; single propeller independently mounted for tests involving changes in propeller position.

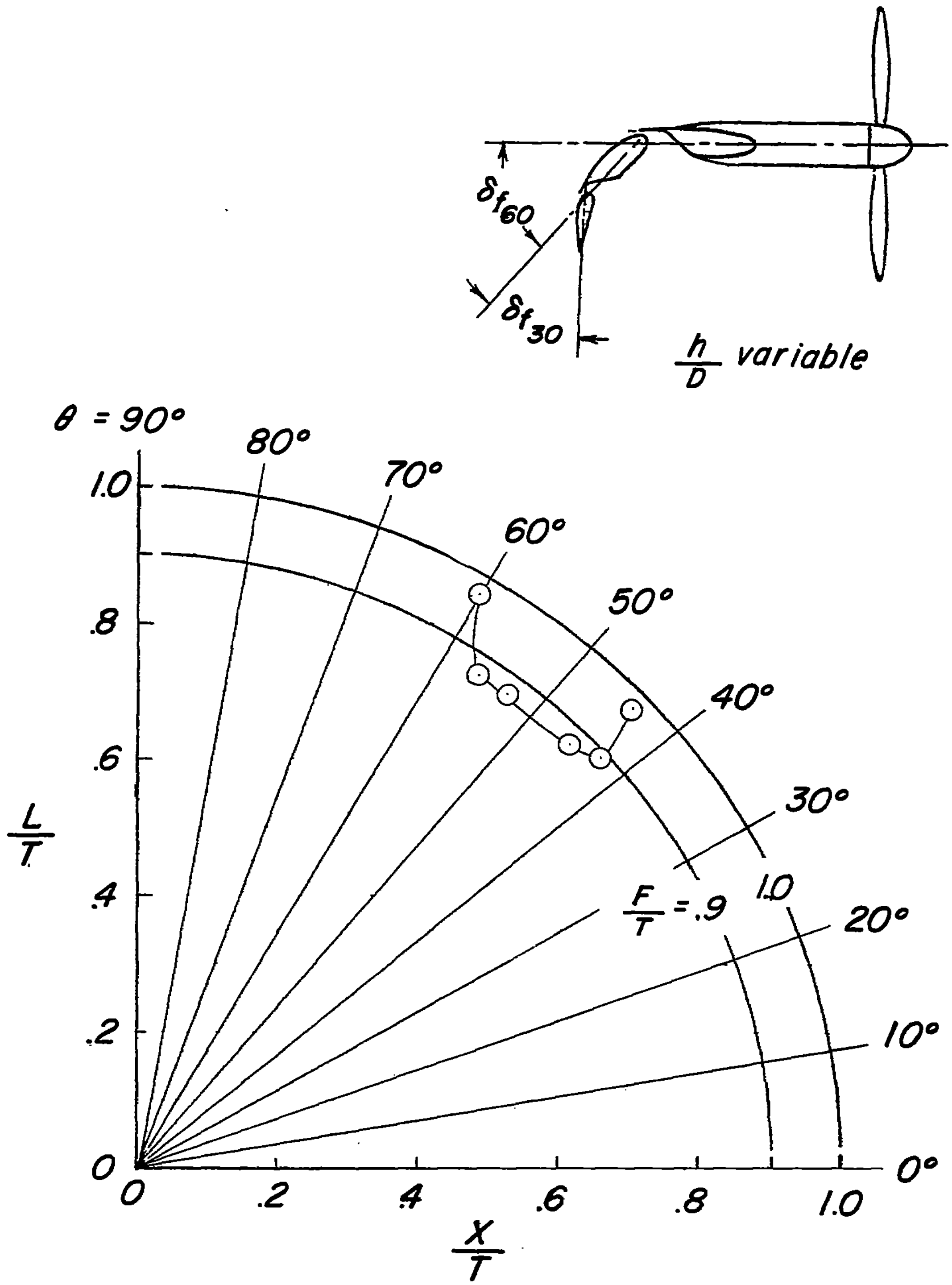


(b) Pitching moment.

(a) Turning angle.

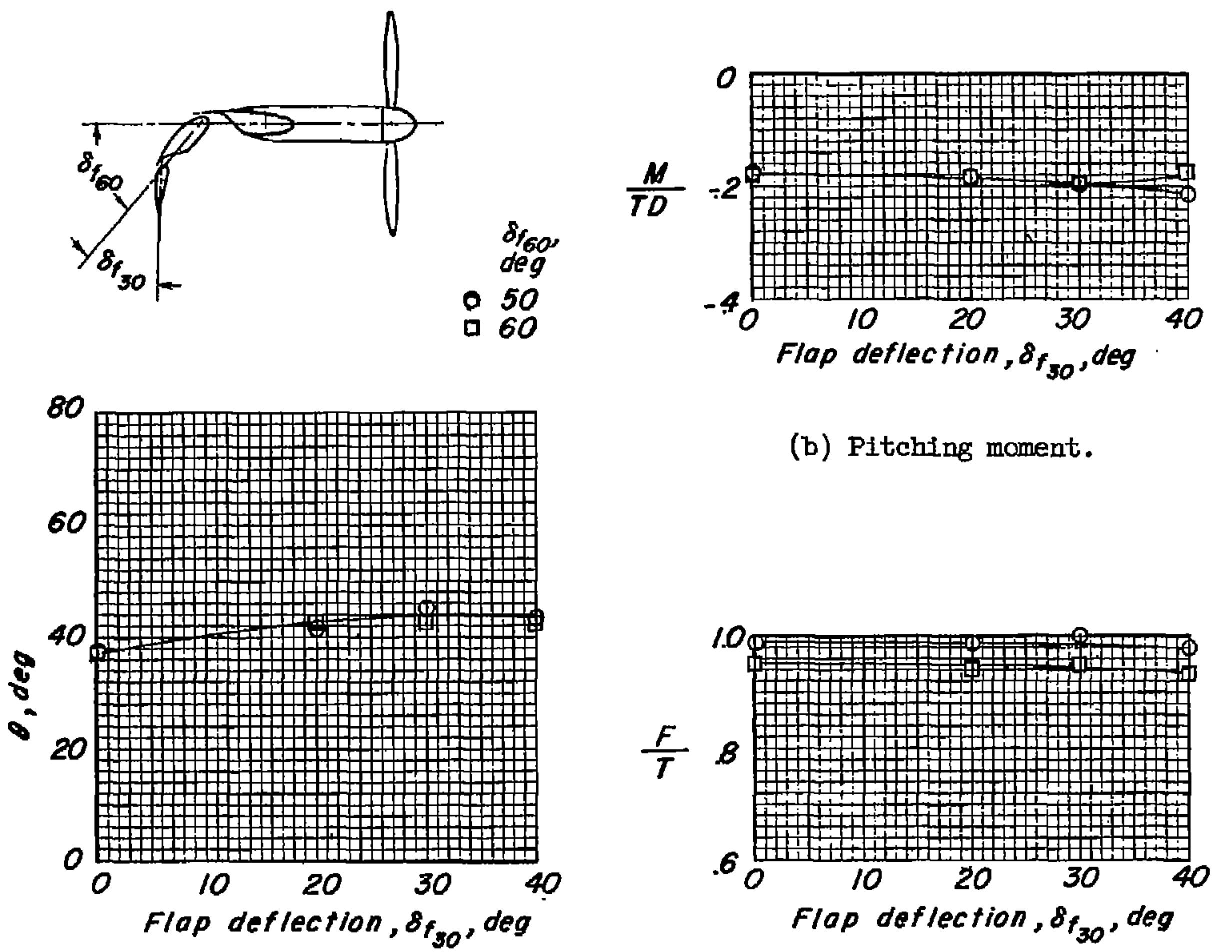
(c) Ratio of resultant force to thrust.

Figure 6.- Effect of height above the ground on the characteristics of the basic slotted-flap configuration. $\delta_{f_{60}} = 50^\circ$; $\delta_{f_{30}} = 40^\circ$.



(d) Summary of turning effectiveness.

Figure 6.- Concluded.

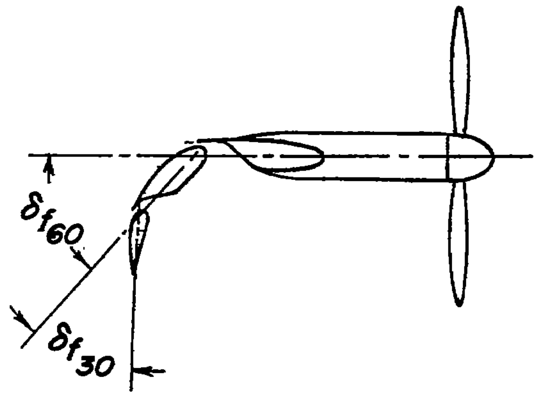


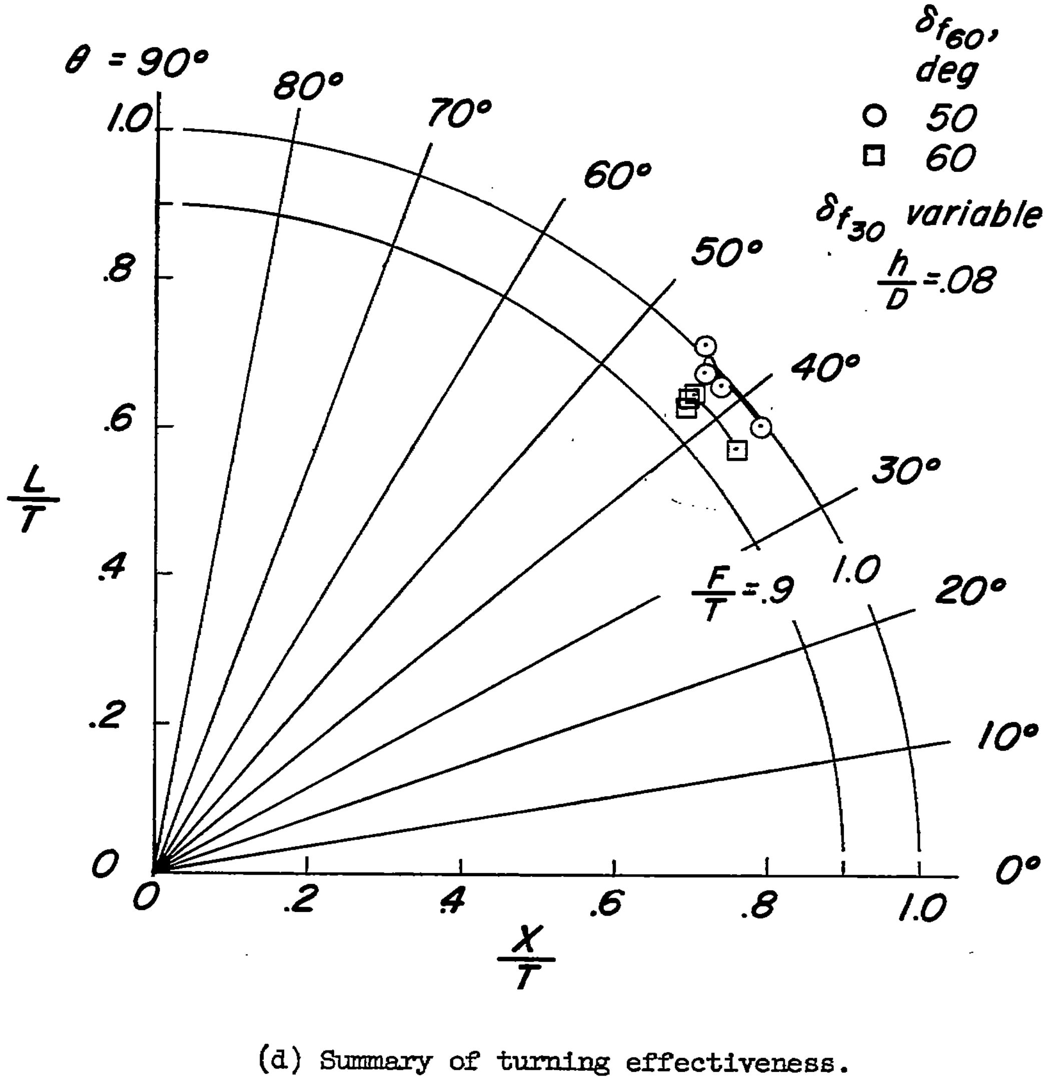
(a) Turning angle.

(b) Pitching moment.

(c) Ratio of resultant force to thrust.

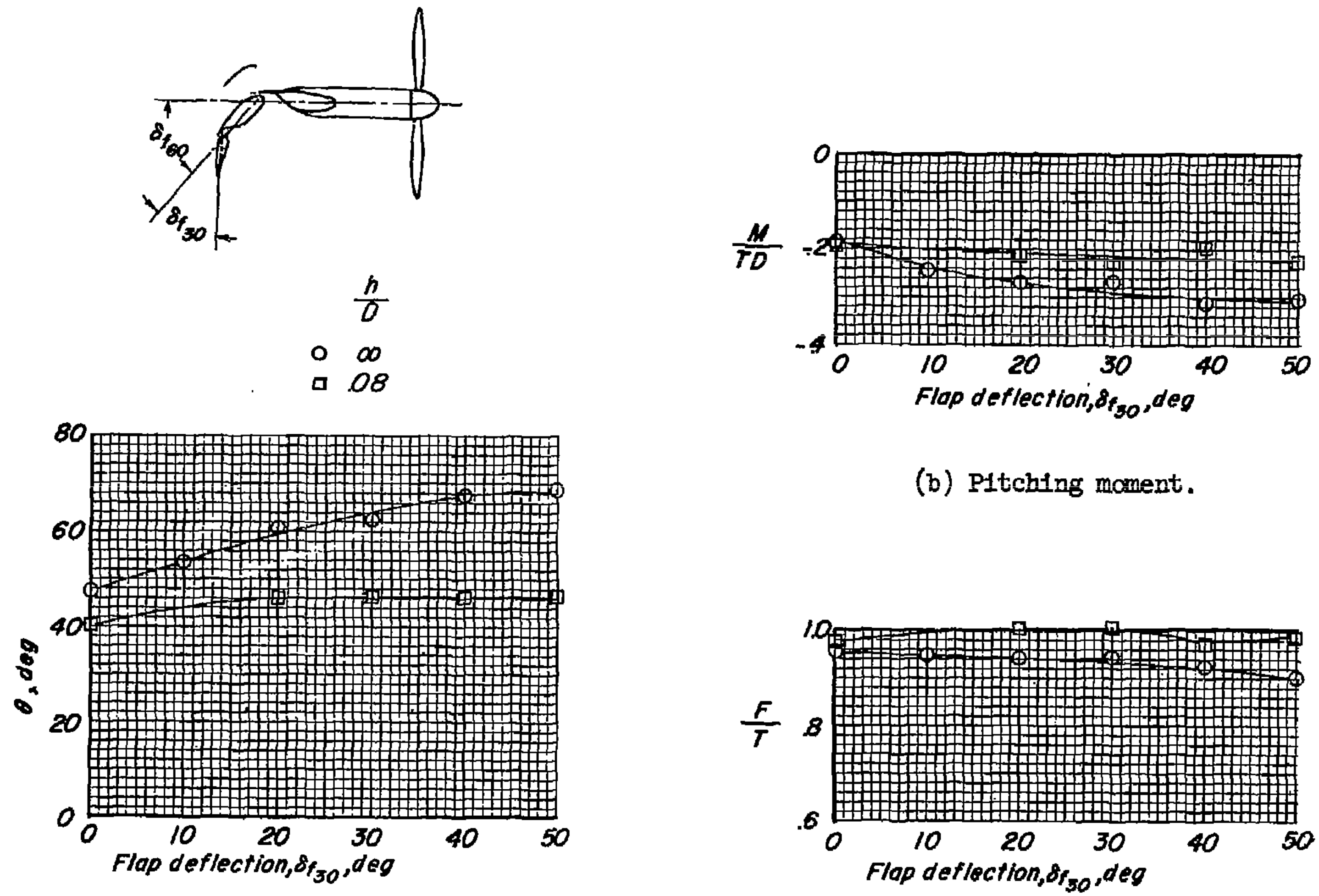
Figure 7.- Effect of flap deflection on the turning characteristics near the ground. $\frac{h}{D} = 0.08$.





(d) Summary of turning effectiveness.

Figure 7.- Concluded.

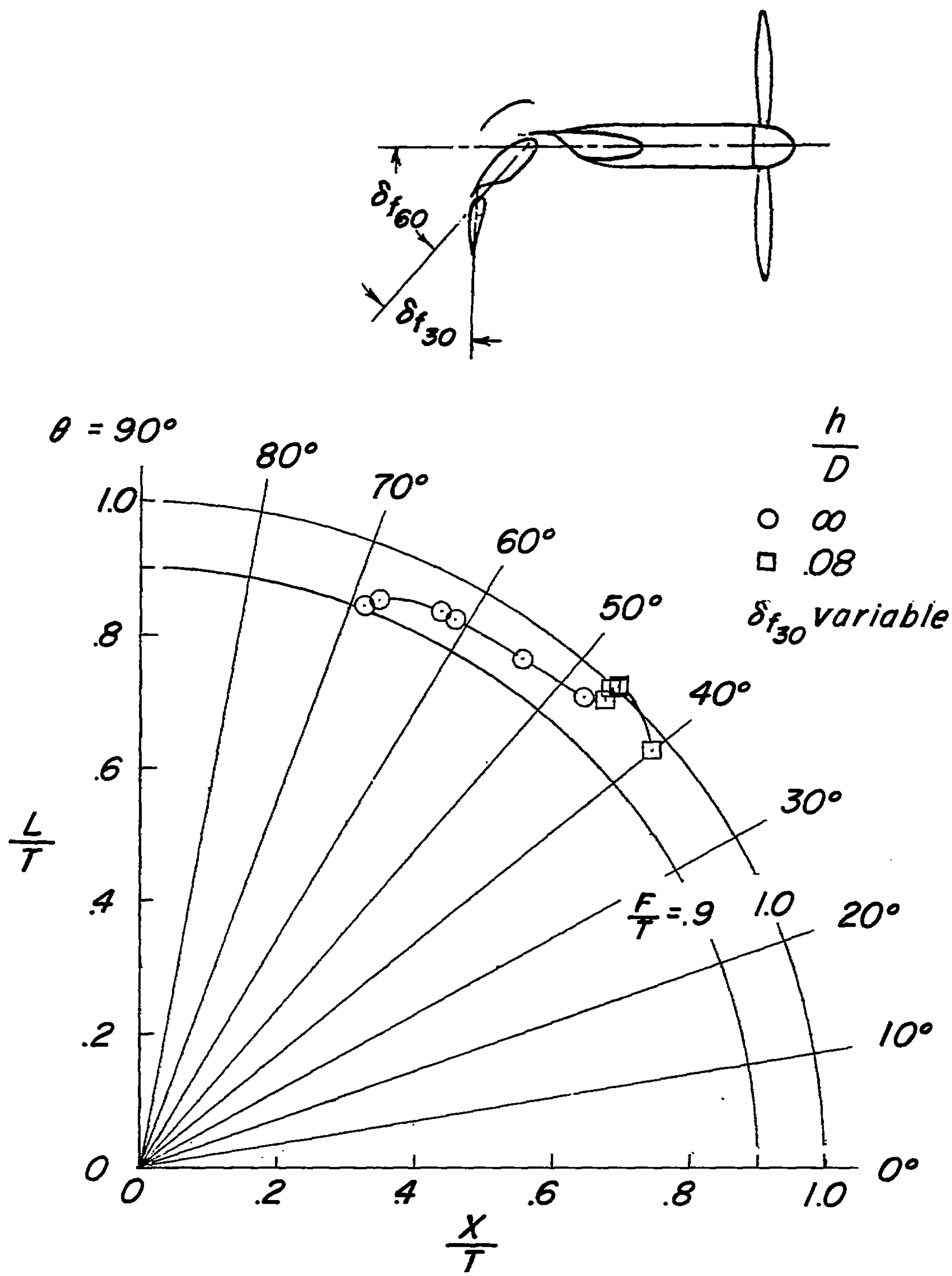


(a) Turning angle.

(b) Pitching moment.

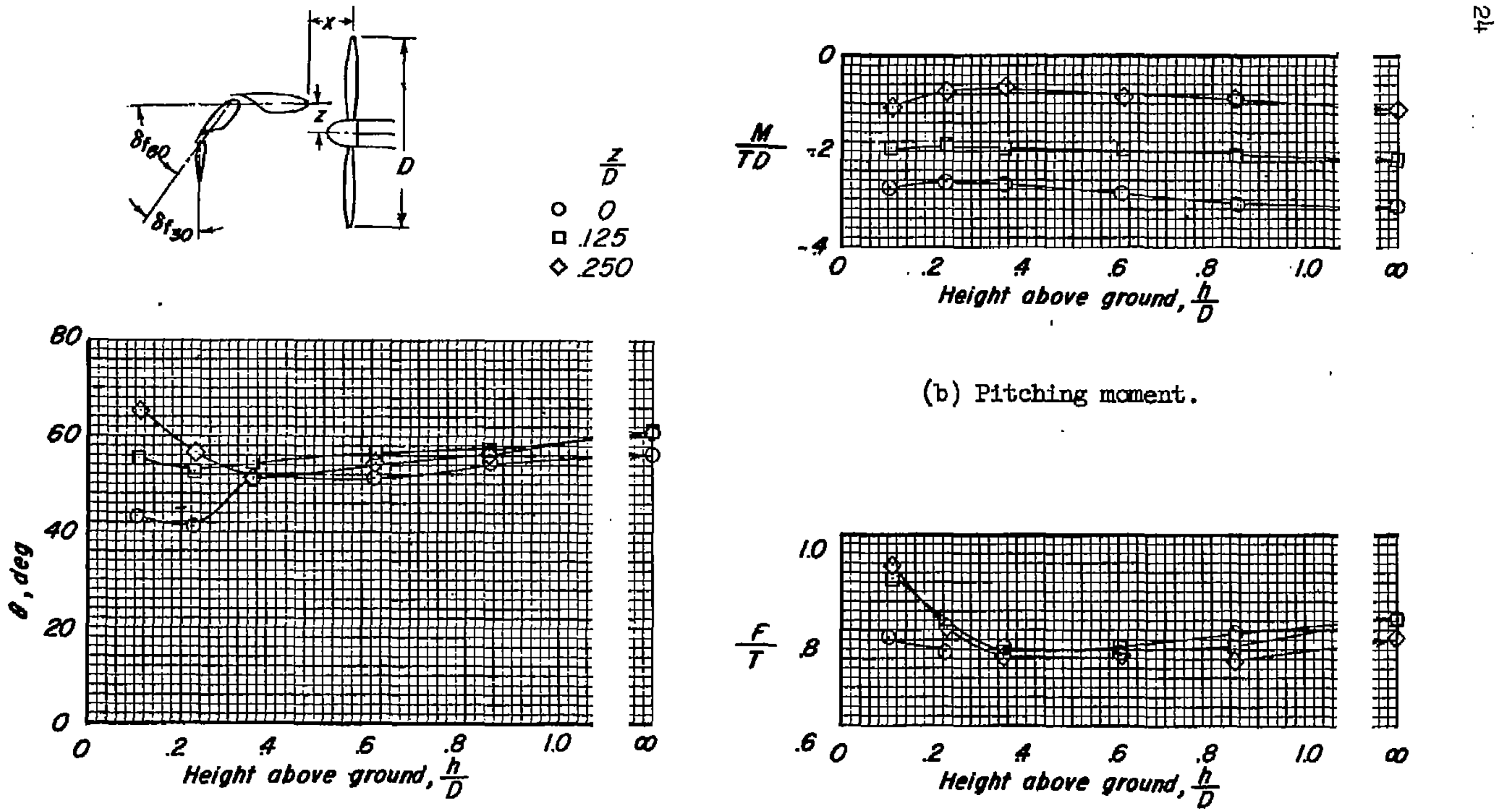
(c) Ratio of resultant force to thrust.

Figure 8.- Effect of flap deflection on the characteristics in and out of the ground-effect region with the auxiliary vane installed. $\delta_{f_{60}} = 60^{\circ}$.



(d) Summary of turning effectiveness.

Figure 8.- Concluded.

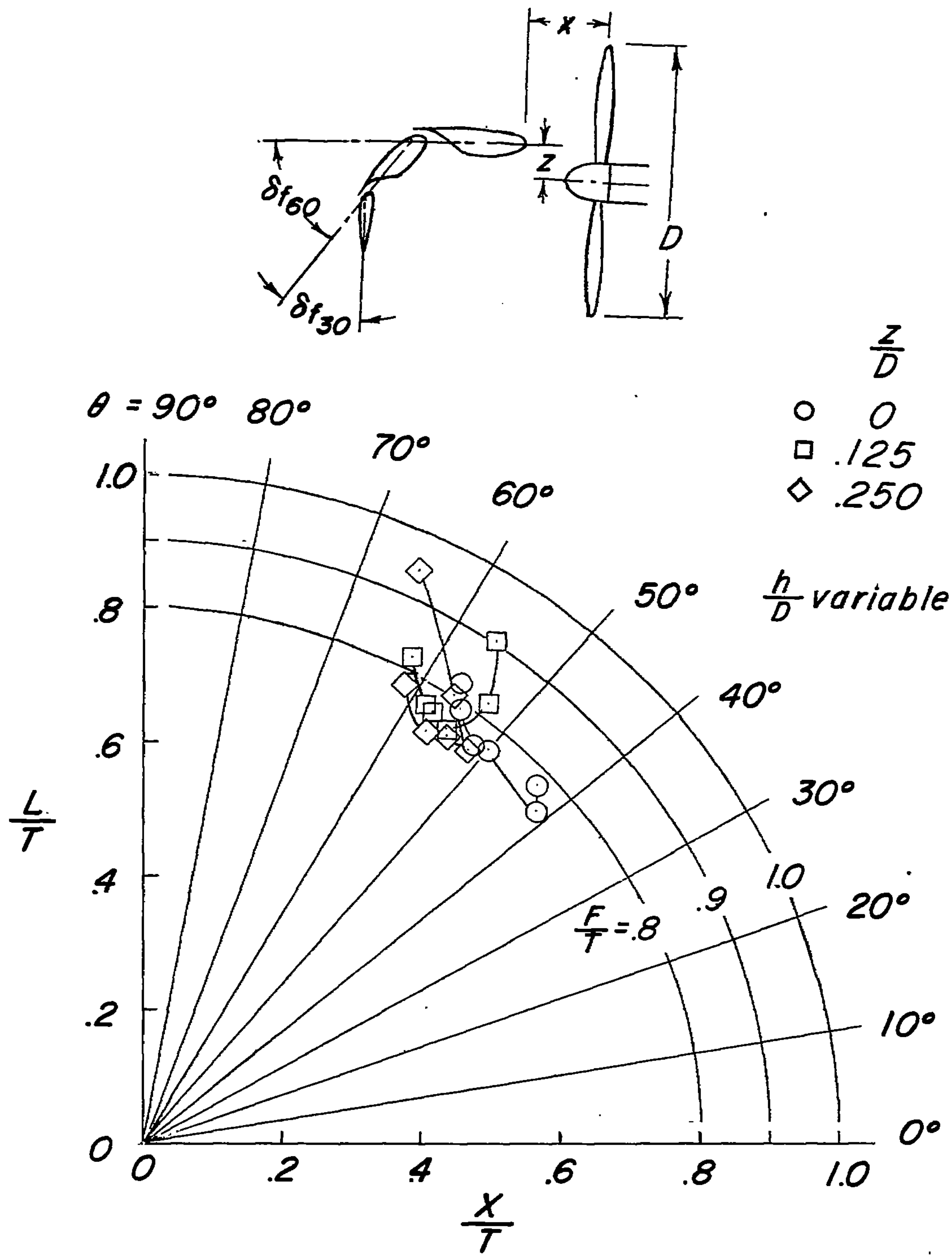


(a) Turning angle.

(b) Pitching moment.

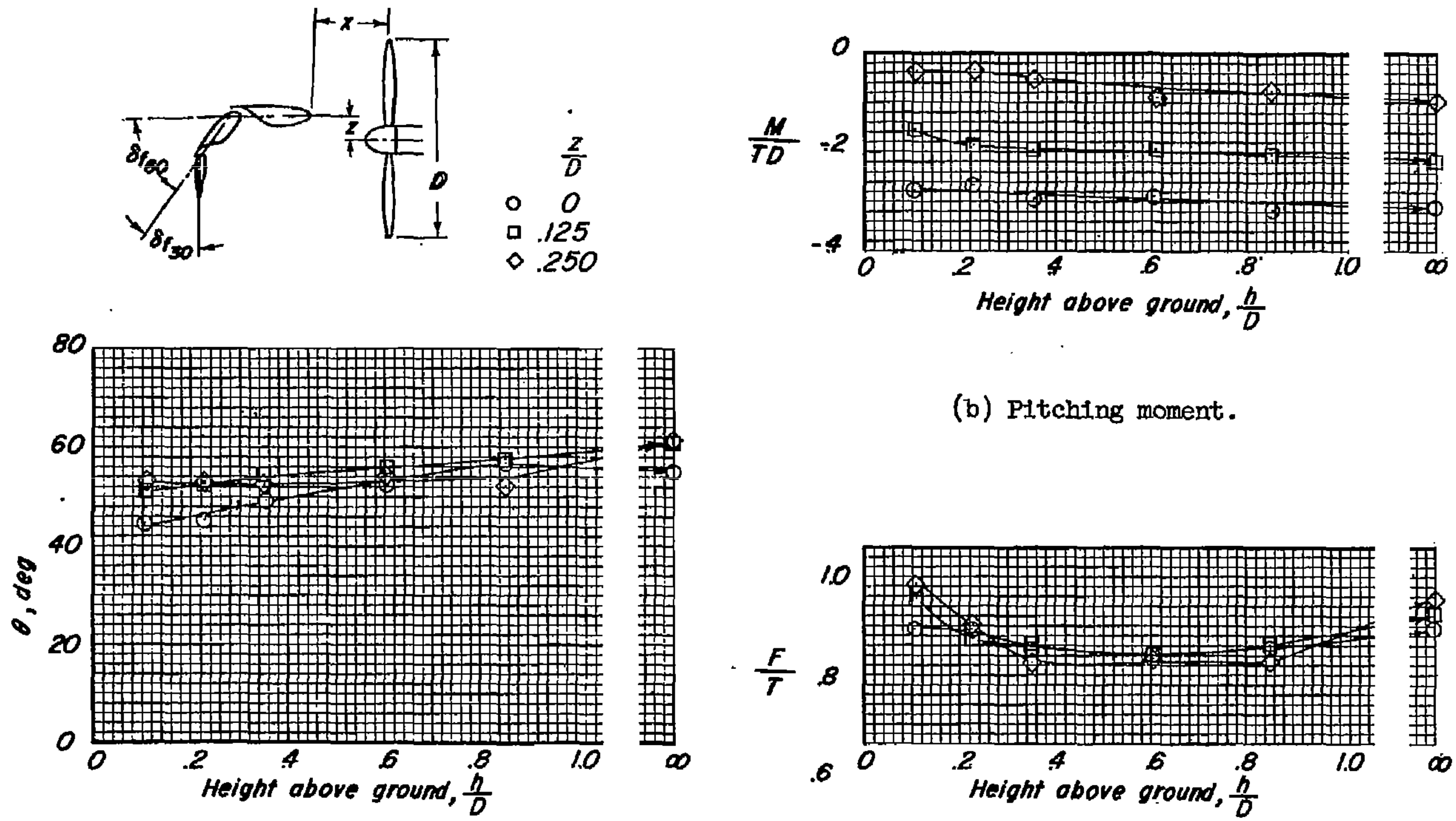
(c) Ratio of resultant force to thrust.

Figure 9.- Effect of vertical position of the propeller on the variation of characteristics with height above the ground. $\delta_{f_{60}} = 50^{\circ}$; $\delta_{f_{30}} = 40^{\circ}$; $\frac{x}{D} = 0.25$.



(d) Summary of turning effectiveness.

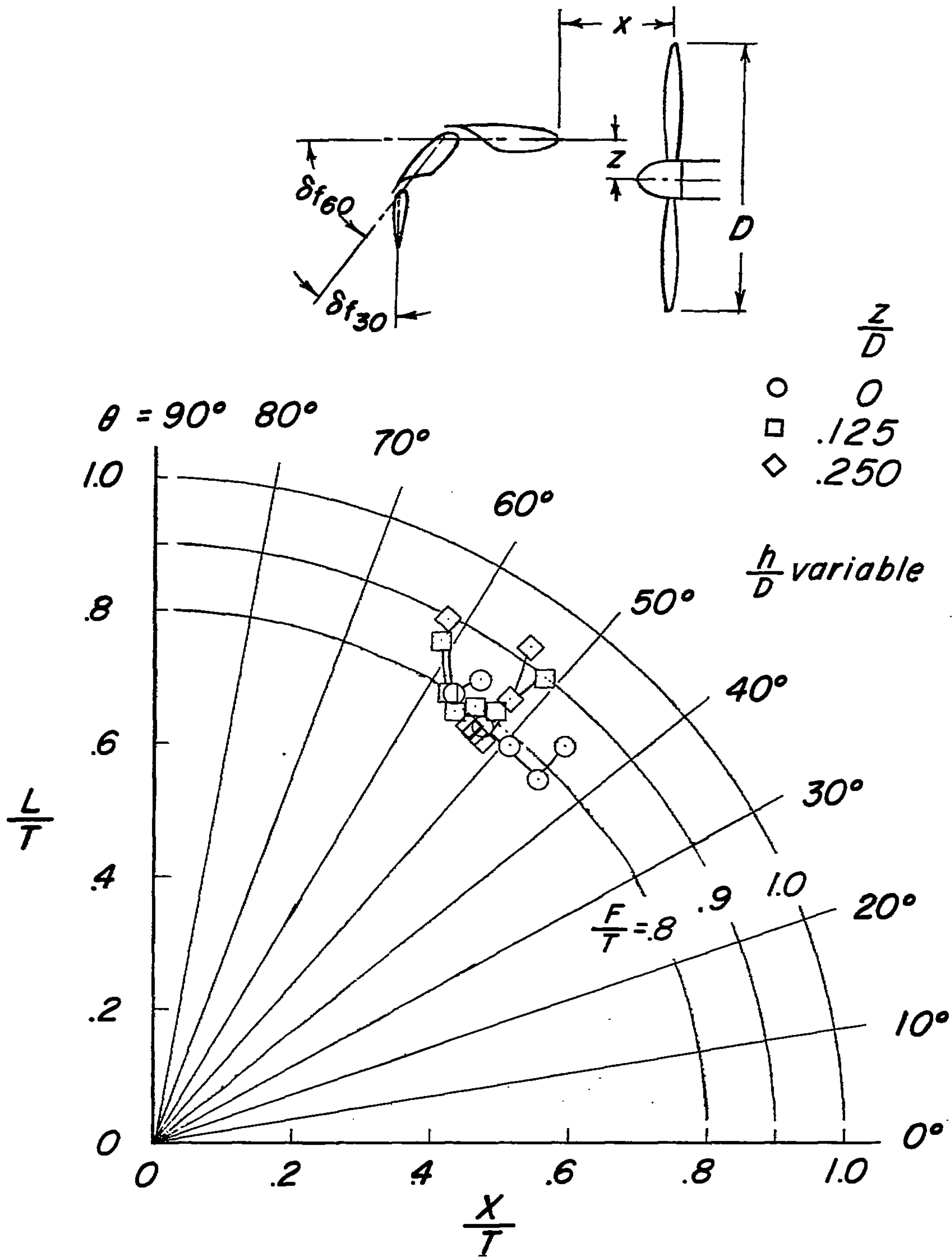
Figure 9.- Concluded.



(a) Turning angle.

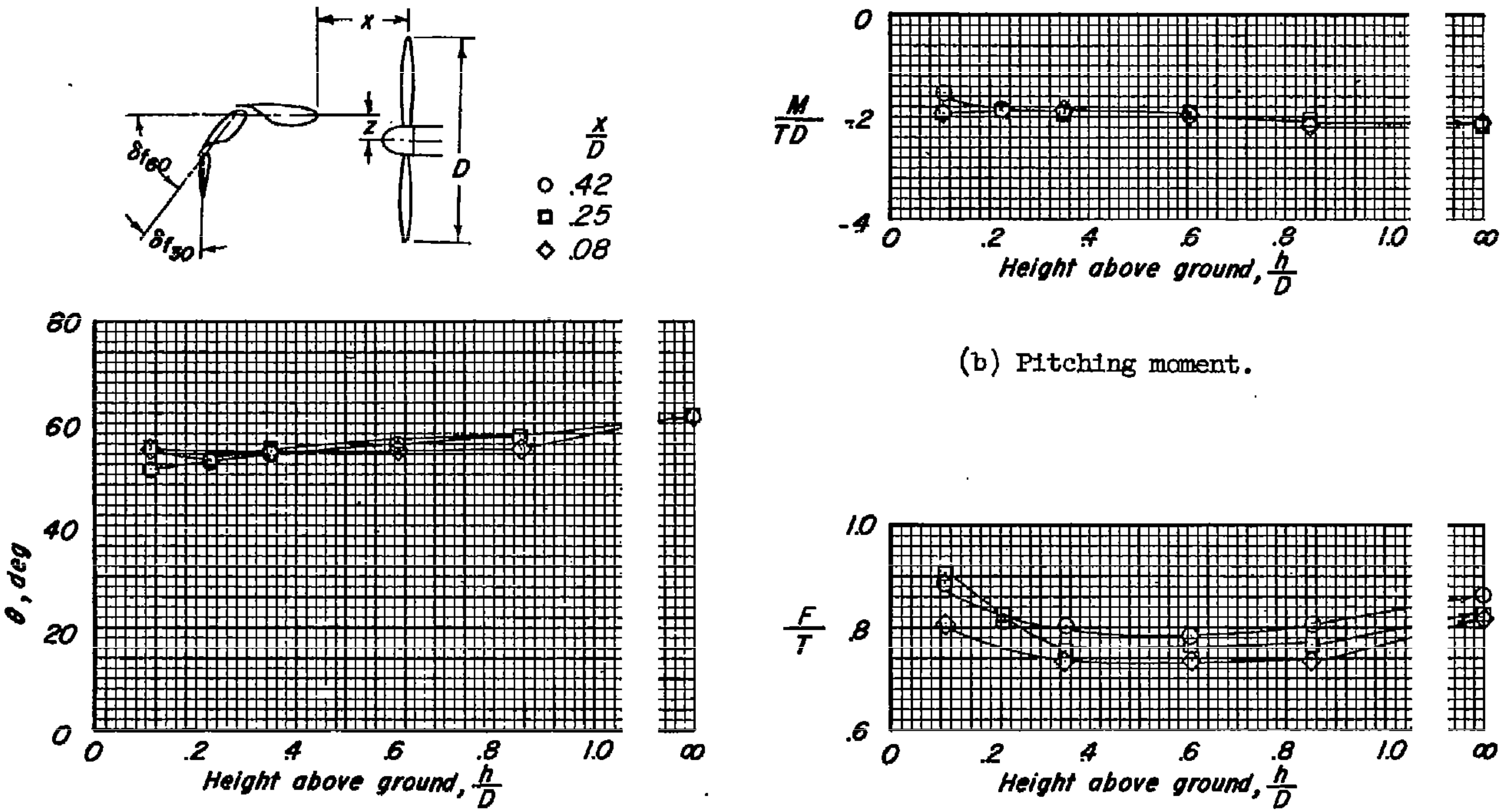
(c) Ratio of resultant force to thrust.

Figure 10.- Effect of vertical position of propeller on the variation of characteristics with height above the ground. $\delta_{f_{60}} = 50^{\circ}$; $\delta_{f_{30}} = 40^{\circ}$; $\frac{x}{D} = 0.42$.



(d) Summary of turning effectiveness.

Figure 10.- Concluded.

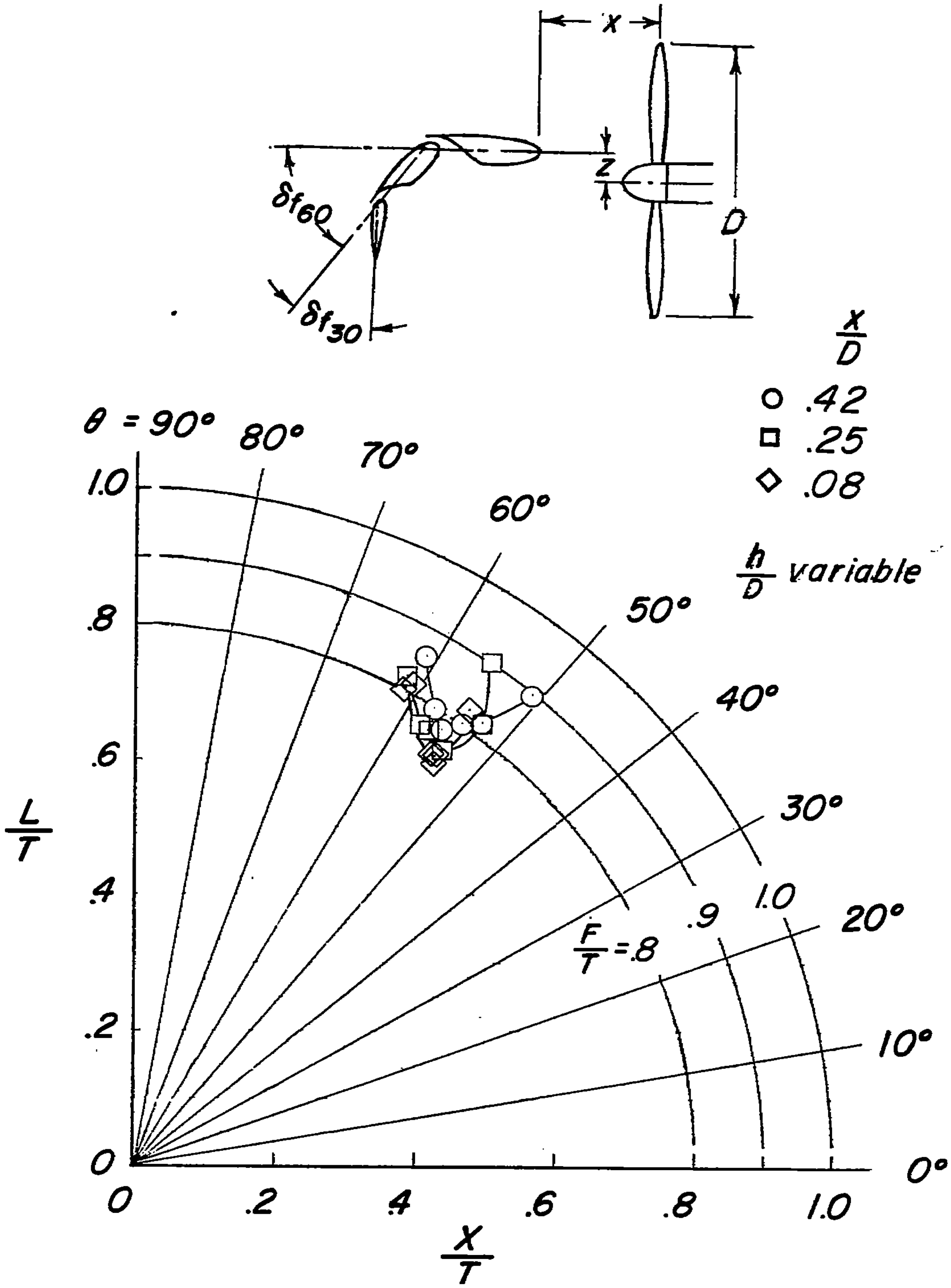


(b) Pitching moment.

(a) Turning angle.

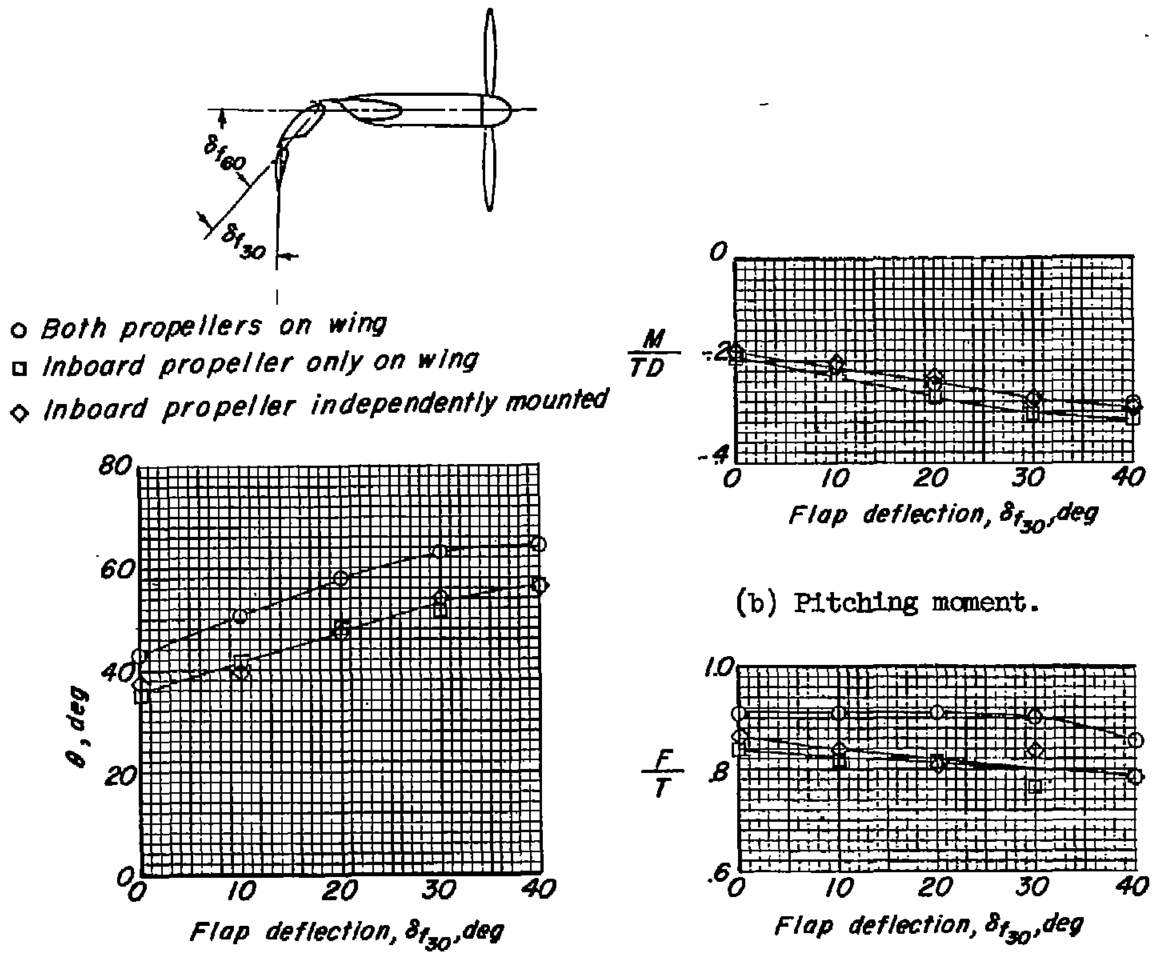
(c) Ratio of resultant force to thrust.

Figure 11.- Effect of longitudinal position of propeller on the variation of characteristics with height above the ground. $\delta_{f_{60}} = 50^{\circ}$; $\delta_{f_{30}} = 40^{\circ}$; $\frac{z}{D} = 0.125$.



(d) Summary of turning effectiveness.

Figure 11.- Concluded.

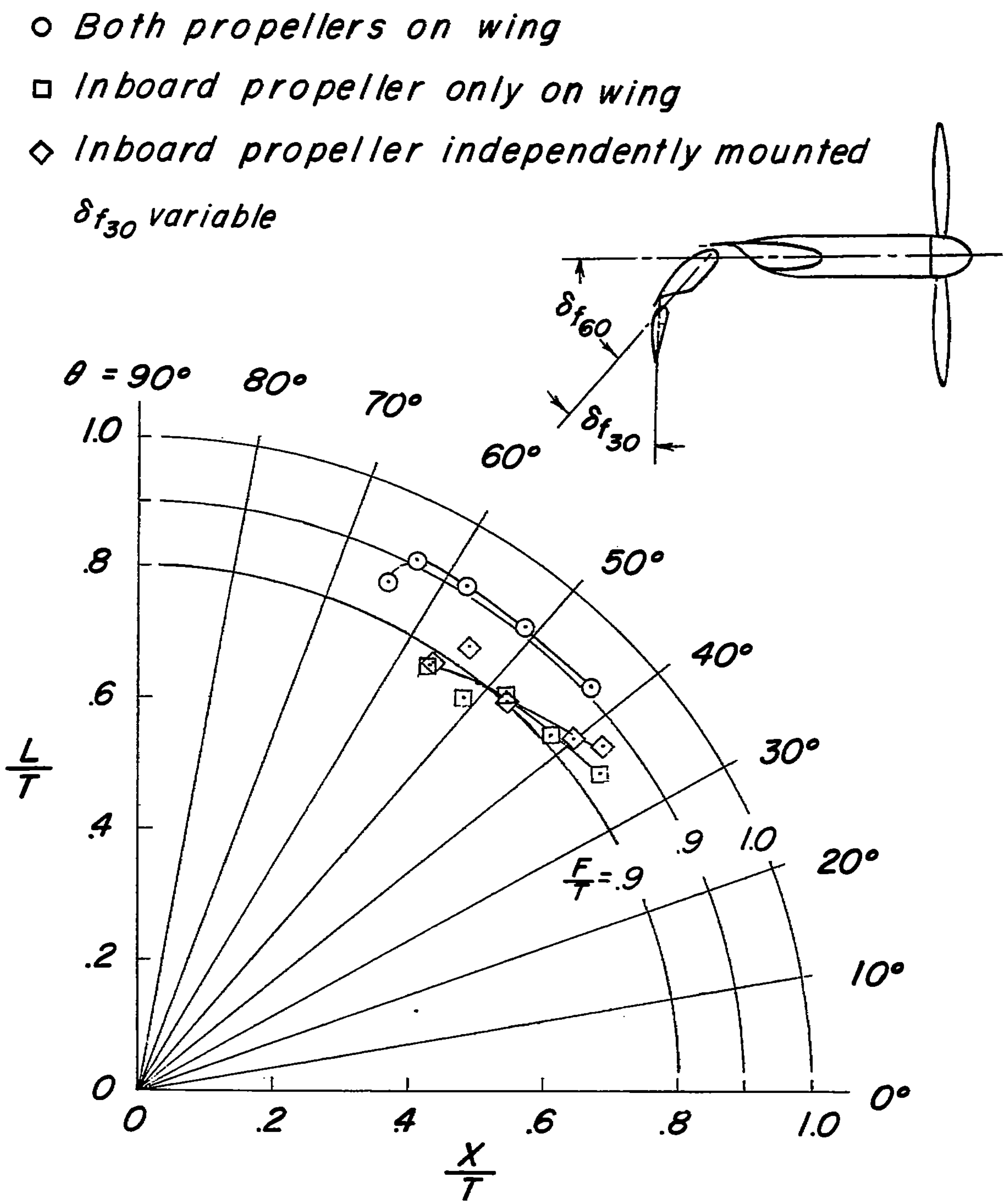


(a) Turning angle.

(b) Pitching moment.

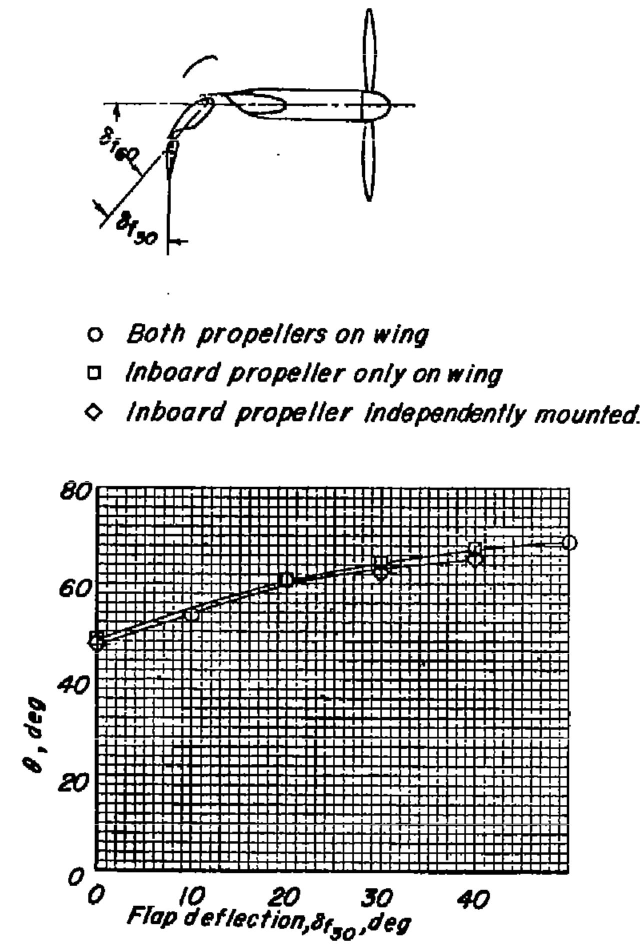
(c) Ratio of resultant force to thrust.

Figure 12.- Comparison of effect of flap deflection on the characteristics with one and two propellers. $\delta_{f_{60}} = 60^{\circ}$; vane off; $\frac{h}{D} = \infty$.

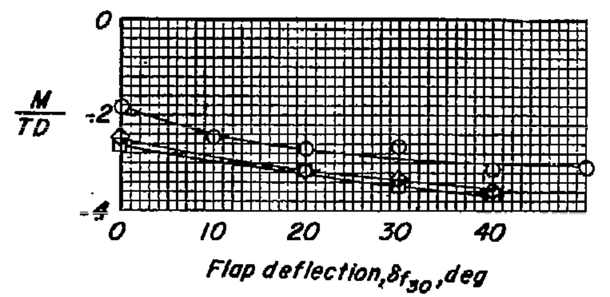


(d) Summary of turning effectiveness.

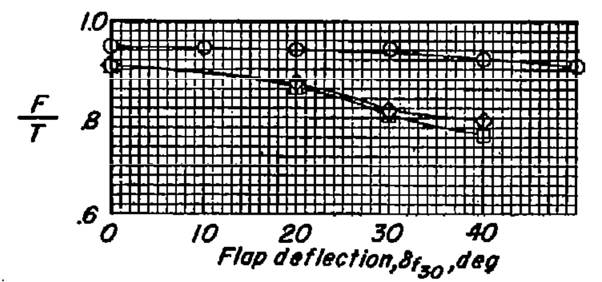
Figure 12.- Concluded.



(a) Turning angle.

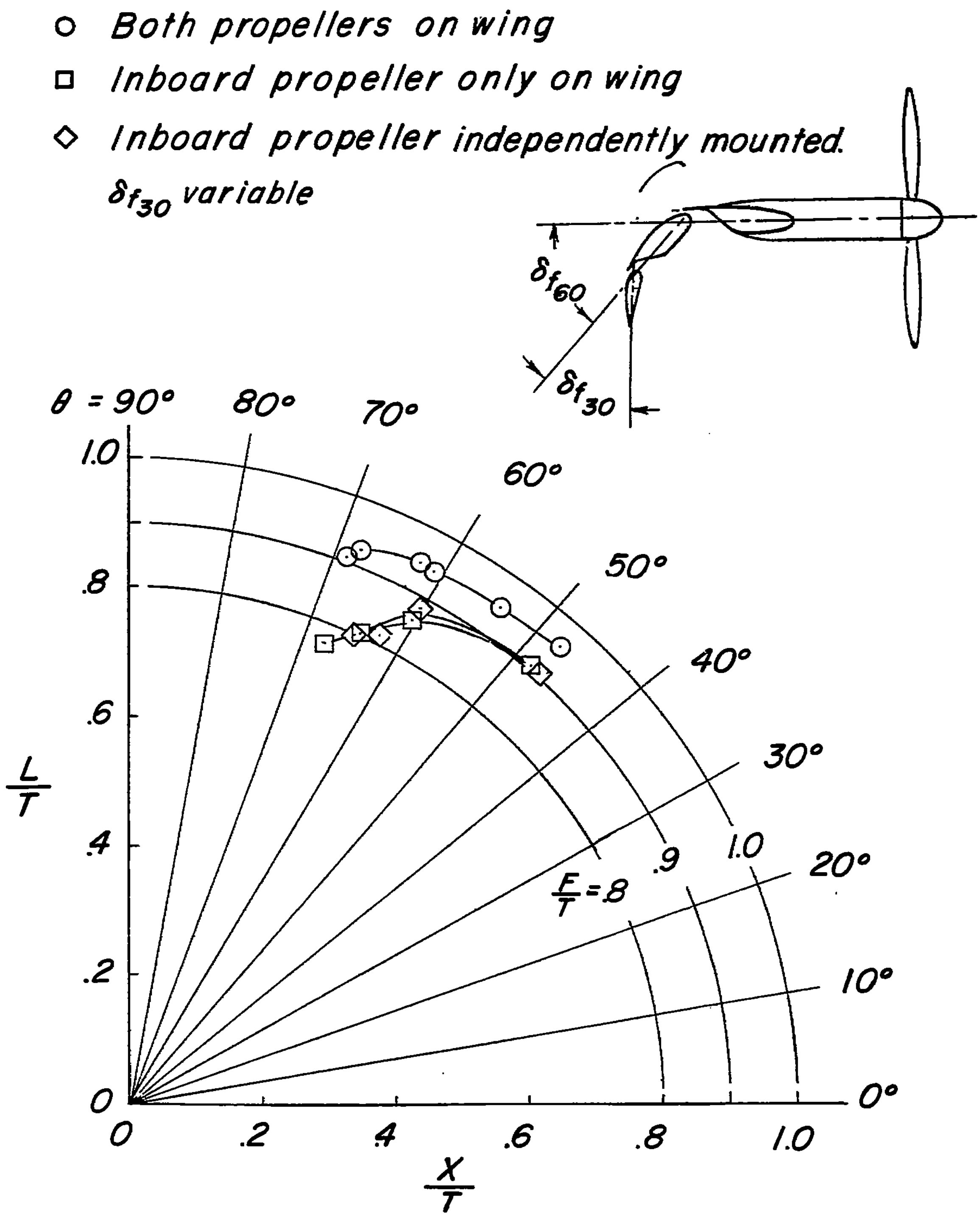


(b) Pitching moment.



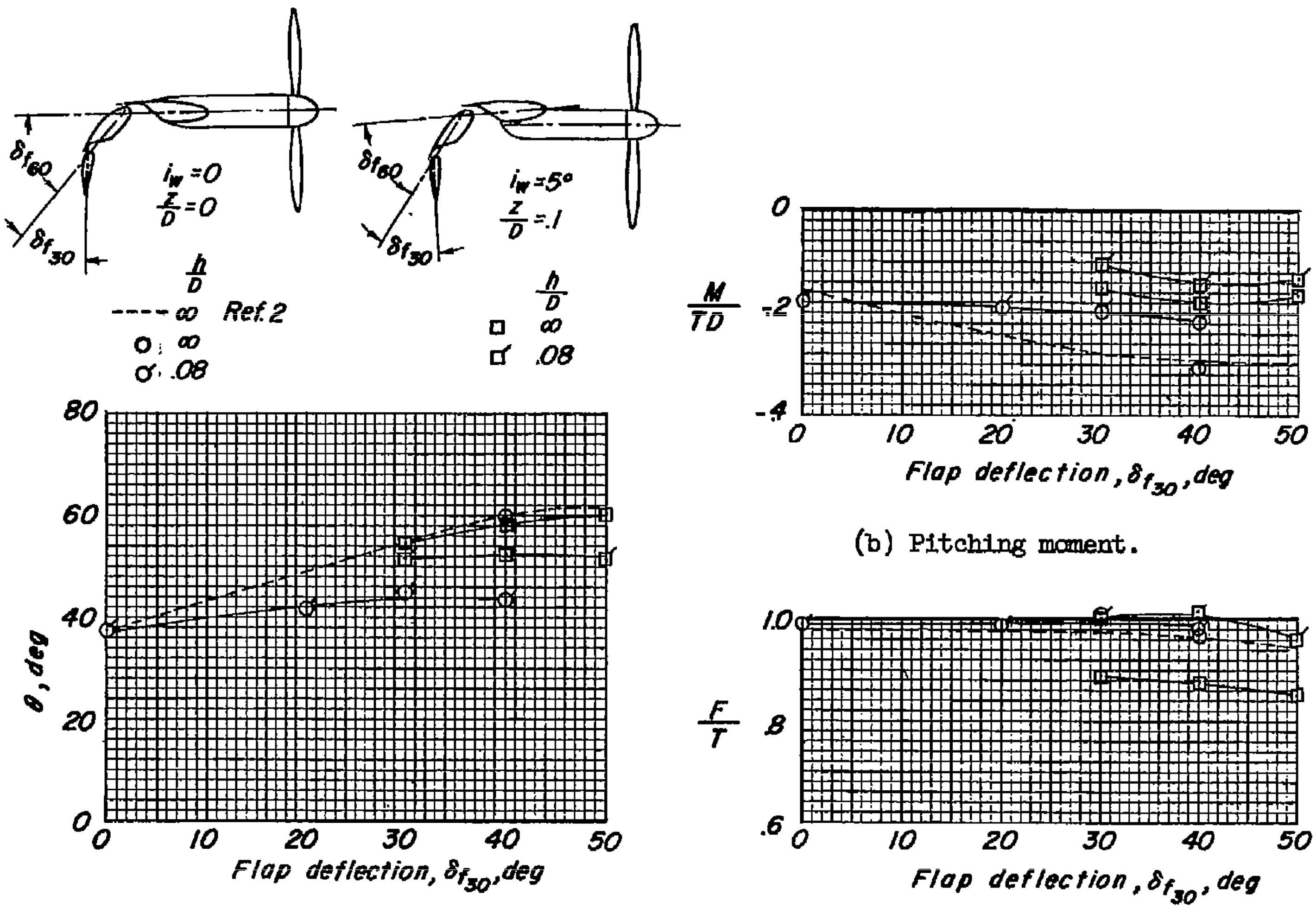
(c) Ratio of resultant force to thrust.

Figure 13.- Comparison of effect of flap deflection on characteristics with one and two propellers. $\delta_{f_{60}} = 60^{\circ}$; vane on; $\frac{h}{D} = \infty$.



(d) Summary of turning effectiveness.

Figure 13.- Concluded.

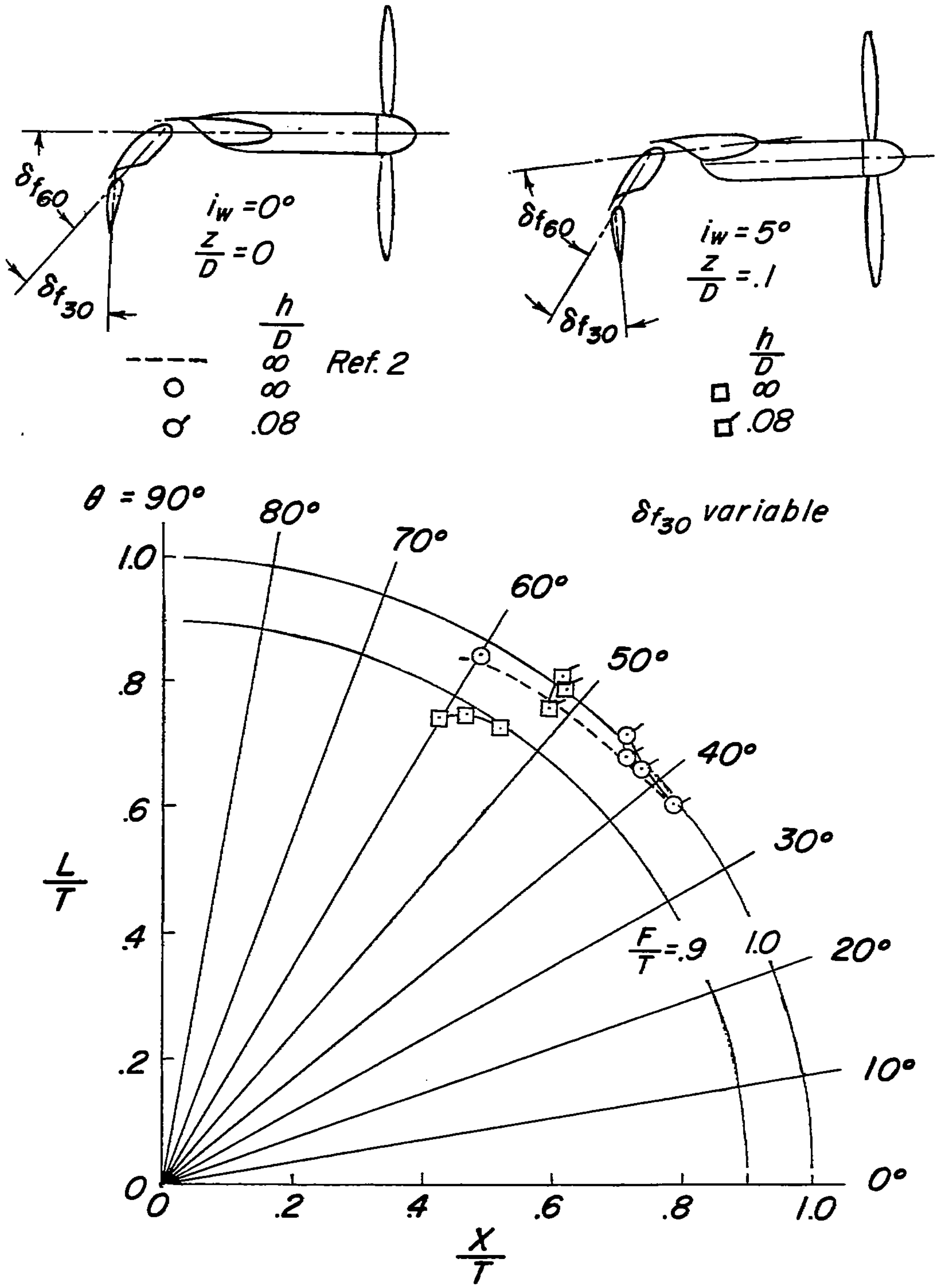


(b) Pitching moment.

(a) Turning angle.

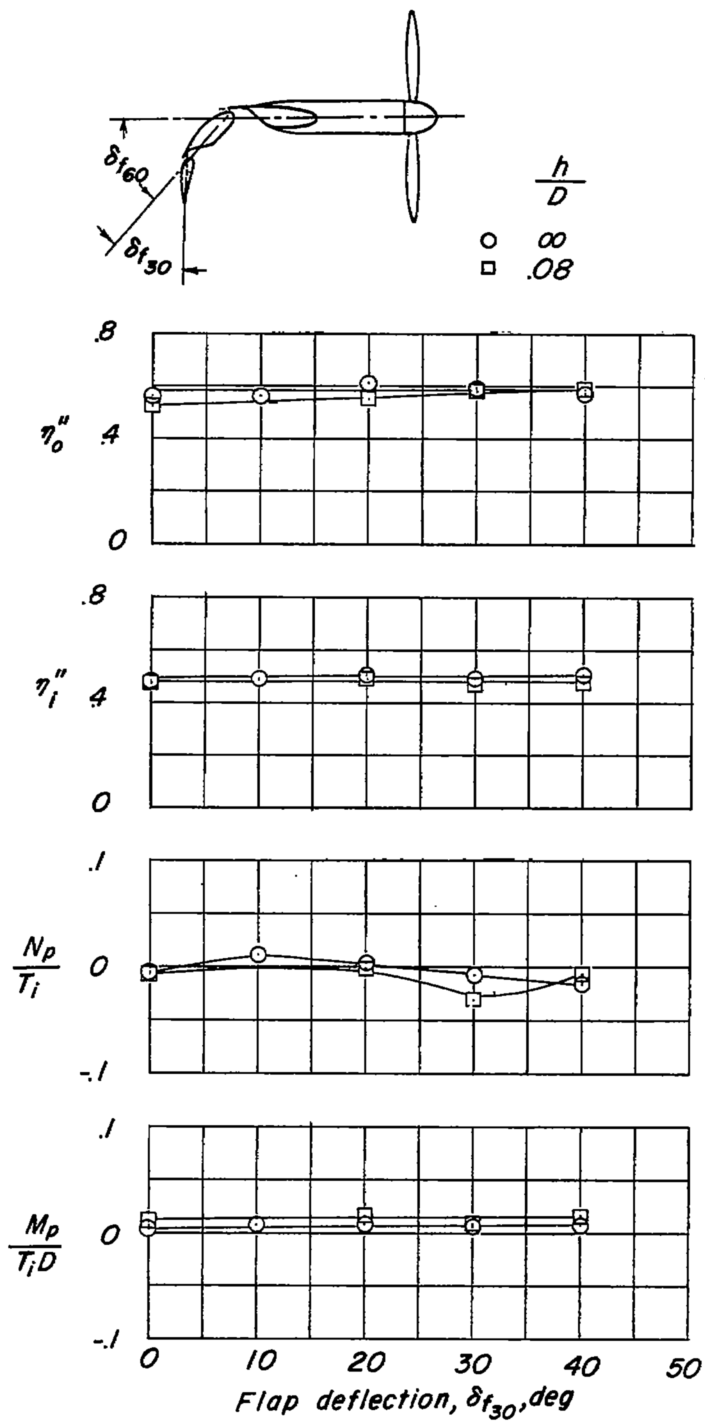
(c) Ratio of resultant force to thrust.

Figure 14.- Comparison between effects of flap deflection on the characteristics of model with the thrust axis on the wing chord plane and with the thrust axis 0.1D below the wing chord plane. $\delta_{f_{60}} = 50°$.



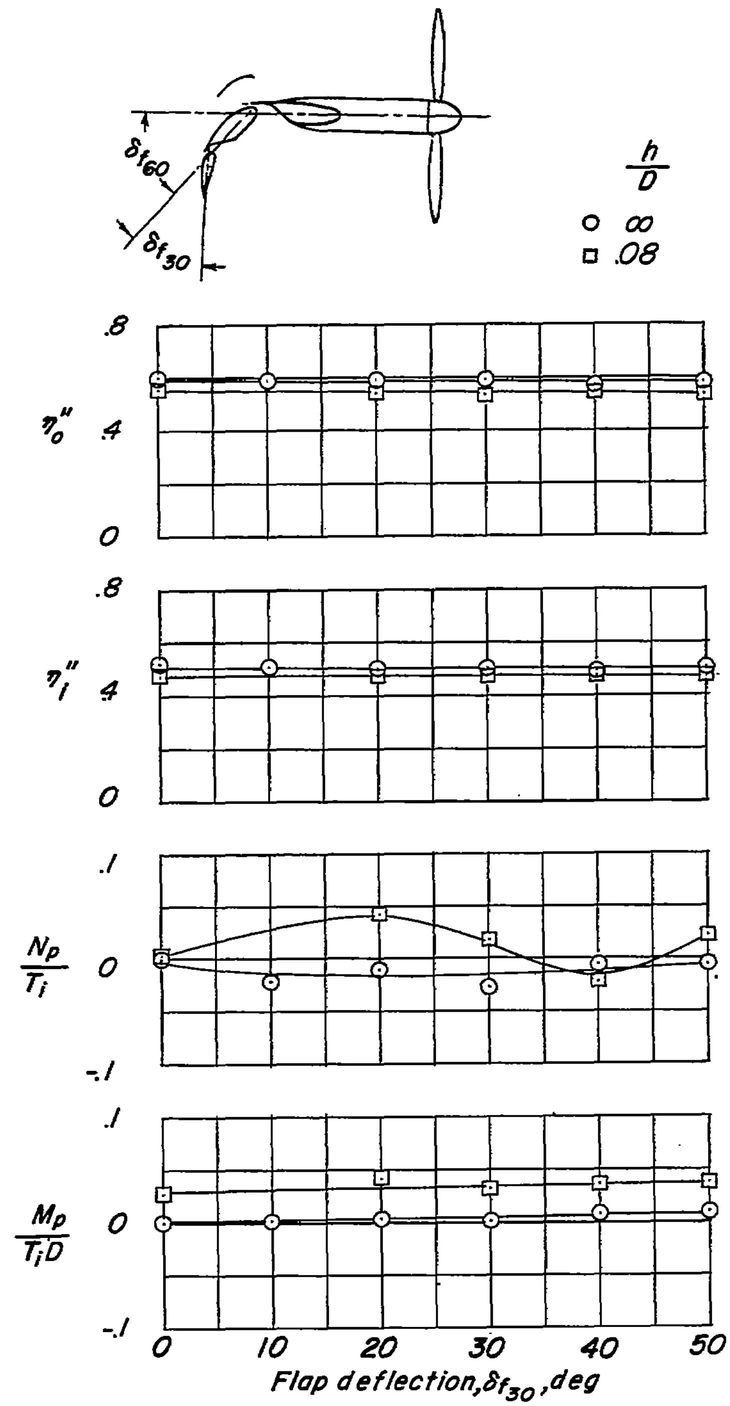
(d) Summary of turning effectiveness.

Figure 14.- Concluded.



(a) Vane off.

Figure 15.- Effect of height above ground on propeller characteristics, $\delta_{f_{60}} = 60^{\circ}$.



(b) Vane on.

Figure 15.- Concluded.

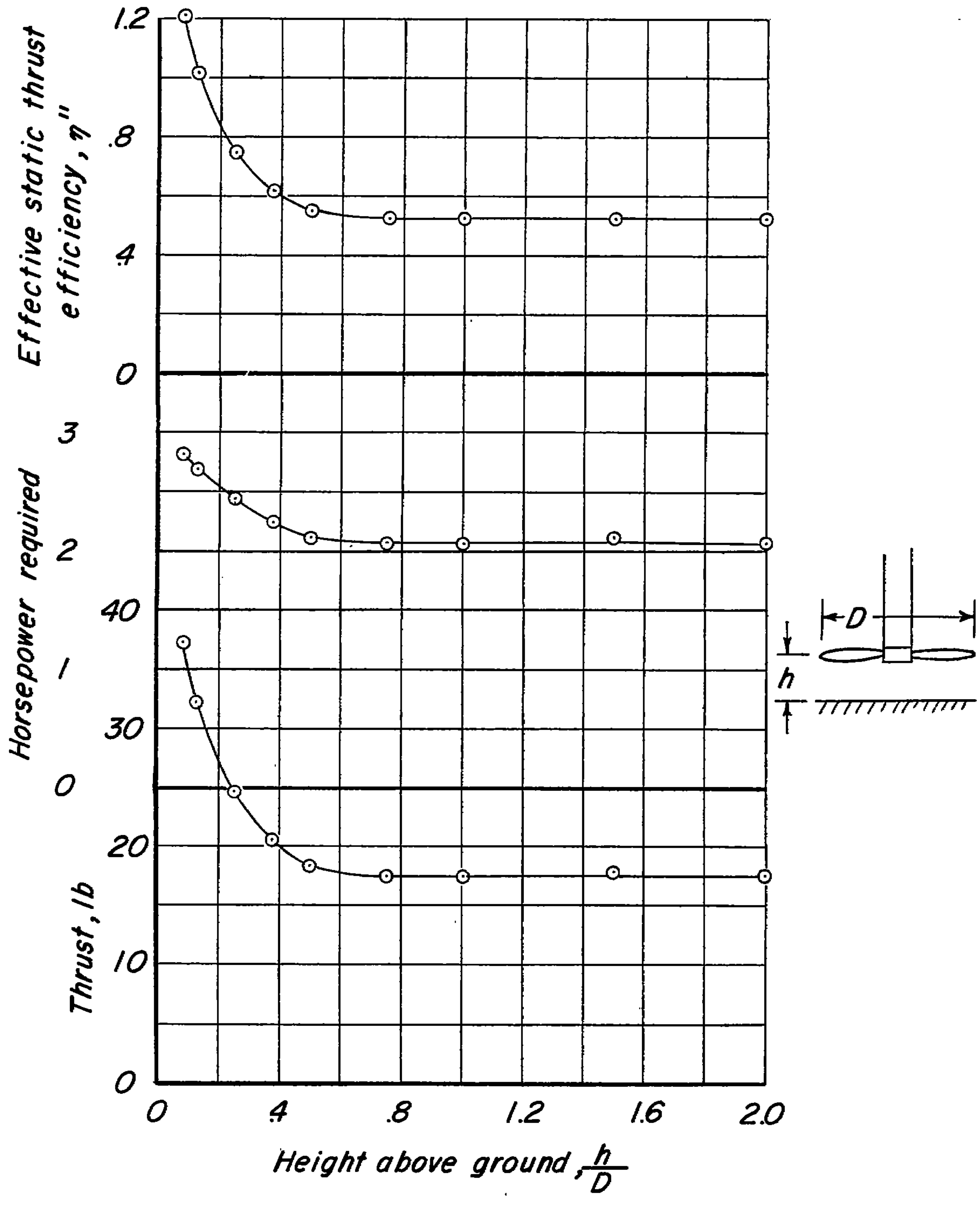


Figure 16.- Effect of height above ground on propeller with the thrust axis perpendicular to the ground.